**TITLE:** Prolonged exposure to monosodium glutamate in healthy young adults decreases perceived umami taste and diminishes appetite for savory foods

**AUTHORS:** Corinna A Noel[1], Graham Finlayson[2], Robin Dando[1]

**AFFILIATIONS:** [1]Department of Food Science, Cornell University, Ithaca, NY USA; [2]School of Psychology, University of Leeds, Leeds UK

**CORRESPONDING AUTHOR:** Robin Dando, PhD, Department of Food Science, Cornell University, Ithaca, NY 14853, USA; email robin.dando@cornell.edu; tel 607-254-3319

**LAST NAMES:** Noel, Finlayson, Dando

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**ABBREVIATIONS:** AUC: Area under the curve, gLMS: generalized Labeled Magnitude Scale**,** LFPQ: Leeds Food Preference Questionnaire, MSG: Monosodium glutamate**,** NaCl: Sodium chloride, VAS: Visual analog scale

**Abstract**

Background

Research suggests that increased consumption of sweet, salt, or fat associates with diminished perceived taste intensity and shifted preferences for the respective stimulus. It is unknown whether a similar effect occurs with consumption of umami.

Objective

The aim of the study was to investigate the influence of habitual exposure to umami taste on umami taste perception, hedonics, and satiety.

Methods

58 healthy men (n=16) and women (n=42) participated in a parallel group, randomized controlled study. The normal weight (BMI: 21.8 ± 2.2 kg/m$^2$) group of young adults (22.7 ± 6.2 years) consumed vegetable broth daily for 4 weeks. The broth for the treatment group (n=28) was supplemented with 3.8g monosodium glutamate (MSG), while the control group (n=30) consumed a sodium-matched broth without MSG. Perceived umami taste intensity and discrimination in MSG solutions; liking, wanting, and preference of a variety of umami rich foods; satiation and satiety from an ad-libitum meal; and anthropometry were evaluated at baseline and week 4. General linear models assessed the effect of treatment on the change from baseline of all outcomes and tested for effect modification of sex.

Results

Relative to the controls, increased consumption of MSG for 4 weeks diminished umami taste in females (8.4 [95% CI: -13.8, -3.1], P=0.013). The desire for and intake of savory foods decreased after MSG treatment in both sexes at an ad-libitum meal (desire: -7.7 [-13.7, -1.7], P=0.04; intake: -36g [-91, 19], P=0.04).

Conclusions

Our results highlight that a month-long diet high in umami stimuli attenuates perceived umami taste and appetite for savory foods in a young, healthy population. Our findings contribute to understanding food choice, a factor in the development and maintenance of obesity, as well as the etiology of protein-related health conditions such as osteoporosis and kidney disease. This study is registered at clinicaltrials.gov (NCT03010930).

**Keywords**: Taste; diet; appetite; sex differences; umami; psychophysics; perception; obesity; monosodium glutamate; randomized controlled study

## Introduction

Experimental and observational studies provide evidence that increased dietary consumption of sweet, salt, or fat associates with diminished perceived intensity of the stimulus, shifting preference to higher concentrations with prolonged exposure (1–3). Research suggests that adaptive changes occur within the sensory systems with repeated exposure to stimuli, decreasing sensory responses, and ultimately requiring more intense stimulation to elicit the same response (1,2,4,5). Specific to the taste system, supplementation of the diet with highly sweetened beverages for one month is linked with altered sweet taste and preference (3), while a low sugar diet increases perceived sweet intensity after three months (6). A high salt diet increases preferred concentration of salt after just three weeks (2), while a low salt diet increases perceived saltiness and decreases preferred concentrations of salt within two months (7). Likewise, a high fat diet decreases fat sensitivity, while a low fat diet increases sensitivity after a four week treatment (1), possibly due to altered expression of the putative fat taste sensor transporter CD36 (8).

While sweet, salt and fat have been routinely studied, umami is the least-characterized taste, despite being highly relevant to our diet, food choices, and metabolic health. There is limited research on umami taste perception and its connection to diet (9), with epidemiological studies investigating taste often entirely lacking an assessment of umami (10,11). Umami taste is thought to signal the ingestion and regulation of protein and amino acids (12–14), and may be linked to body weight maintenance, obesity, and satiation (13–19). Frequently described as savory or meaty, umami taste is elicited strongly by the presence of glutamate or glutamic acid (20,21). Although glutamates are naturally abundant in many foods (19,22,23), a common and powerful stimulus of umami taste in the human diet is monosodium glutamate (MSG). Some evidence suggests that the body may not effectively distinguish added MSG from dietary glutamate (20). While high protein foods are naturally high in umami taste (24), gustatory and hedonic responses to MSG have also been linked to dietary protein (12,25).

We tested the hypothesis that repeated consumption of an umami-rich, MSG-supplemented stimulus in healthy adults would decrease perceived umami intensity and hinder the ability to discriminate low concentrations of umami, and further would alter hedonics, food preferences, and satiation. We report a randomized controlled study, where participants in the treatment group supplemented their diet for 4 weeks with a broth containing the umami-rich stimulus MSG, while participants in the control group consumed the same broth, sodium-matched but without the added MSG.

**Methods**

The Cornell University Institutional Review Board approved all aspects of this study. The protocol is registered at clinicaltrials.gov (NCT03010930).

Design and participants

A parallel group, single blinded randomized controlled study design with 1:1 allocation examined habituation to umami taste in October and November 2016. Based on the variation observed in taste after controlled dietary changes in Wise et al. (6) and research in our lab, a power calculation suggested that a sample size of 50 would detect a 30% difference in perceived taste intensity between groups at $\alpha=0.05$ with a power of $1-\beta=0.80$.

Potential participants were recruited by contacting prior study participants at the Cornell University Sensory Evaluation Center via email and by advertising with flyers on campus. A prescreening questionnaire assessed eligibility, excluding those that were hypertensive or on a low sodium diet, smokers, those reporting an allergy to MSG, nuts, or dairy, those classified as a restrained eater (score > 12 on the dietary restraint subscale of Three Factor Eating Questionnaire (1,26)), vegans, frequent consumers of Asian foods, those under the age of 18 years or over the age of 55 years, and those outside of a healthy BMI range of 18.5-25.0 $kg/m^2$ (27) with self-reported height and weight. These strict exclusion criteria were put in place for the safety of participants and to limit theorized external influences on taste and appetite outcomes such as smoking, age, BMI, and degree of eating restraint.

Participants completed a semi-quantitative food frequency questionnaire (Diet History Questionnaire, DHQ, National Cancer Institute), which provided valid estimates of daily protein and glutamic acid intakes (28). We hypothesized that glutamate may act as a proxy for habitual consumption of umami stimuli, since dietary glutamates are a main source of umami taste in the diet (20). Based on the DHQ estimates, enrolled participants were stratified into groups via median split based on low and high daily glutamic acid consumption (median 12.1 g/day).

A stratified block randomization with a random allocation sequence generation (Sealed Envelope, London, UK) balanced groups by sex (male, female) and habitual glutamic acid consumption (low, high) prior to the start of the intervention. As a single-blinded study, participants were not aware which treatment arm they were in; randomly assigned numbers identified both participants and treatment groups.

Treatments

Participants consumed one cup (237 ml) of low glutamate vegetable broth (Vegebase, Vogue Cuisine Foods) daily for four weeks. The treatment group's broth was supplemented with 3.8g MSG, equivalent to increasing the average US daily dietary glutamate consumption by 20% (29). The control group's broth contained no added MSG, but was sodium-matched with 1.8g NaCl to ensure both broths contained the same amount of sodium. Both broths contained 15 kcal, 0.3g fat, 2g carbohydrates, 1g protein, and 615 mg sodium. Bench testing confirmed both broths were palatable, and that neither was out of the ordinary for the taste of traditional broths. Intensity and liking ratings of the broth were captured in the first and last week of the 4-week intervention with the generalized Labeled Magnitude Scale (gLMS) and hedonic gLMS.

To ensure adherence to the study protocol, participants were required to pick up and consume the prepared broth at a central location within one hour after lunch, and attendance was taken daily. Participants were provided with prepackaged powdered broth on weekends and consumed broth remotely. Text message reminders and brief surveys to assess study adherence were sent every day that broth was consumed remotely (TXT Signal, Inc., Gainesville, FL).

Testing session outline

All outcomes were evaluated at baseline and immediately after the 4-week intervention at the Cornell University Sensory Evaluation Center. No broth was consumed on the day of testing and participants were directed to abstain from eating and drinking 3 hours prior to the lunchtime session (30). Testing took place between 11:00AM and 2:00PM and individuals completed both pre- and post-intervention sessions in the same time slot to minimize any time-of-day effects. The baseline and post-treatment testing sessions followed the same procedure with ample breaks throughout to minimize fatigue: anthropometric measurements, training in scale usage, basic taste evaluations, Leeds Food Preference Questionnaire, ranking task, and hedonics and preference of real foods, followed by a two-course ad-libitum test meal. Electronic questionnaires captured responses during testing sessions using RedJade sensory software (Tragon, San Francisco, CA).

Taste measures: intensity and discrimination

Participants received training on the generalized Labeled Magnitude Scale (gLMS, (31,32)), rating a series of broadly varying auditory and visual, real and imagined sensations. After correctly ranking the last set of remembered sensations (33), whole mouth suprathreshold taste intensity ratings for aqueous umami, sweet, and salty stimuli were captured on the gLMS, with scale descriptors and values as follows: no sensation (0.0), barely detectable (1.4), weak (6.0), moderate (17.0), strong (34.7), very strong (52.5), and strongest imaginable sensation of any kind (100.0). Aqueous taste stimuli were prepared in deionized water and were presented twice, separately, in a series of three ascending concentrations: sucrose for sweet taste at 27.0, 81.0, and 243.0 mmol/L; sodium chloride (NaCl) for salty taste at 11.1, 33.3, and 100.0 mmol/L; monosodium glutamate (MSG) for umami taste at 3.0, 9.0, and 27.0 mmol/L. Duplicate gLMS ratings were averaged with an arithmetic mean. The randomly numbered solutions were served in pseudo-random blocked order, with a sip and spit procedure (34).

Participants ranked four sodium-matched solutions with varying MSG content (0.0, 3.0, 6.0, and 9.0 mmol/L) according to perceived umami intensity. A rank scoring system based on the methods of Steward et al. (1) assessed the ability to discriminate lower concentrations of MSG, with a higher score indicating greater agreement with actual rank.

Test meal: satiation and satiety measures

An ad-libitum test meal was used to assess satiation and satiety, consisting of two separate courses (30,35,36). Pasta and sauce (spaghetti, Allegra; marinara sauce, Furmano's) was served first as the savory course, while ice cream (vanilla, Cornell Dairy) was served after as the sweet course.

Subjective appetite ratings were assessed throughout the ad-libitum test meal: before the meal, immediately after the savory course, and immediately after the sweet course. Ratings on 100-point visual analog scale (VAS) for six dimensions of appetite: hunger (‘How hungry are you?’; 0=Not at all, 100=Extremely), fullness (‘How full are you?’; 0=Not at all, 100=Extremely), satiety (‘How satiated are you?’; 0=Not at all, 100=Extremely), prospective consumption (‘How much do you think you could eat right now?’: 0=Nothing at all, 100=A very large amount), desire for savory (‘How strong is your desire to eat something savory?’; 0=Extremely low, 100=Extremely high), desire for sweet (‘How strong is your desire to eat something sweet?’; 0=Extremely low, 100=Extremely high) (30).

### Liking, wanting, and preference measures

Participants consumed small samples of a variety of real foods (Parmesan cheese, Wegmans brand; unsalted dry roasted almonds, Sincerely Nuts; sundried tomato, California Sun Dry; strawberry jam, Wegmans brand; dill cucumber pickles, Wegmans brand). Hedonic ratings were captured on the hedonic gLMS (37), a bipolar scale with similar descriptors and values to the gLMS, ranging from greatest imaginable disliking of any kind (-100.00), to neutral (0.0), to greatest imaginable liking of any kind (100.00).

Liking and wanting for high protein foods was evaluated for four outcomes (explicit liking, explicit wanting, relative food preference, and implicit wanting) using the Leeds Food Preference Questionnaire (LFPQ), as described previously (38–40). The LFPQ is sensitive to month-long changes in diet (38) and has been associated with food choices and intake in a free-living environment (40). 16 foods of varying protein content (low: <7% protein; high: >15% protein) and taste (sweet or savory) were presented on a computerized program. For each outcome, mean scores for the low protein foods were subtracted from the high protein foods to provide a measure of the 'appeal' for high protein foods (41), with a greater score signifying a greater appeal for high protein foods.

A demographic questionnaire captured information on sex, age, and ethnicity. Body height (cm) and weight (kg) were measured with a stadiometer and digital scale, following standard procedures (42). BMI was calculated with the formula: BMI=[weight (kg) / height$^2$ (m)].

## Statistical analysis

General linear models assessed the effect of treatment on change from baseline in taste intensity, liking, wanting, satiation, and appetite sensations. The change outcomes can be interpreted as an increase (positive value) or decrease (negative) from baseline. Taste intensity models controlled for usage of the gLMS by including the remembered sensation 'the brightness of the sun on a sunny day' as a covariate, as recommended previously (33). The appeal scores for the LPFQ data (explicit wanting, explicit liking, relative food preference, implicit wanting) were assessed in separate models, each with a random subject effect. Rank analysis of covariance analyzed the change from baseline in umami discrimination from the ranking task scores. Including the interaction term of 'sex x treatment group' assessed effect modification of sex on outcomes; the p-value threshold for assessing effect modification was set at $P<0.10$. All analyses adjusted for baseline value of the outcome, controlling for any inherent group differences prior to the intervention.

Data on figures represent mean ± SEM of outcomes, adjusted for baseline value and stratified by treatment group and sex, if it was determined to be an effect modifier. Data in the text show the main effect of treatment with the P-value, while outcomes by treatment group are presented with outcome estimates and 95% confidence intervals (95% CI). Sensitivity analyses were conducted based on adherence to the testing protocol. The analysis was conducted using SAS version 9.4 (SAS Institute Inc., Cary, NC). The threshold for statistically significance was $P<0.05$.

## Results

Participant flow and baseline characteristics

A prescreening questionnaire assessed the eligibility of 240 participants, excluding 132 participants that did not meet the eligibility criteria above and 42 who later declined participation, resulting in a randomization of 66 participants into control and treatment groups (**Figure 1**). 3 people were lost to follow-up in the control group, while 4 people dropped out of the study in the treatment group, citing time constraints or inability to meet the daily attendance requirement. One additional participant in the treatment group failed to follow directions at the testing sessions and thus was excluded from analysis due to missing data.

<Figure 1>

In total, data were analyzed from 58 participants, consisting of 30 in the control group and 28 in the treatment group. The study population overall represented a fairly healthy, normal weight ($21.8 \pm 2.2$ kg/m$^2$) group of young adults ($22.7 \pm 6.2$ years), primarily female (72.4%) and Caucasian (62.1%) (**Table 1**).

<Table 1>

There were no significant baseline differences in age, gender, dietary glutamate, protein intake, race/ethnicity, and restrained eating score between groups. Regardless of treatment group, males tended to report a greater daily intake of protein (M: 88.4g±17.2; F: 65.4g±4.6) and dietary glutamate (M: 16.9g±3.1; F: 13.0g±0.9) than females, although not significantly (protein:

P=0.08; dietary glutamate: P=0.10). While the BMI of the treatment group was slightly higher than the control group (control: 21.3 $kg/m^2$ ± 2.2; treatment: 22.5 $kg/m^2$ ± 2.2), both groups were within a normal BMI range (27). To assess any potential confounding influence, baseline BMI was included in the final models assessing the primary and secondary outcomes. Inclusion of BMI as a covariate did not alter regression coefficients, and so the covariate was not included in the analyses presented here.

Controlling for baseline differences, groups did not gain weight differentially across the study period (P=0.65), although males had greater gains in BMI than females (M: 0.37 $kg/m^2$ [0.1, 0.6]; F: -0.03 $kg/m^2$ [-0.2, 0.1]; P<0.01).

Ratings of basic taste intensity

At the start of the intervention, the broth supplemented with MSG tended to be rated as more intensely umami on average compared to the control broth (control: 20.2 ± 2.5; treatment: 27.7 ± 3.2), although not significantly (P=0.06). Hedonic ratings of the broths were similar at baseline (control: 2.3 ± 3.6; treatment: 10.6 ± 4.2; P=0.14). Following the intervention, liking and intensity did not differ nor change significantly by group when controlling for baseline ratings (umami intensity P=0.96; liking P=0.76), as both groups marginally perceived less umami (control: 3.8 [95% CI: -7.7, 0.2]; treatment: 3.9 [-8.0, 0.2]) and negligibly increased in liking (control: 1.7 [-5.8, 9.1]; treatment: 3.3 [-4.4, 11.0]). There were no differences in hedonic ratings by sex, either at the start or end of the intervention (Wk 1 P=0.53; Wk 4 P=0.54).

After consuming broth for 4 weeks, there was a marginal difference between treatment groups for the highest aqueous stimuli concentration of umami (effect of treatment group: 5.8 [95% CI: -0.7, 12.4], P=0.08), but not for sweet or salty tastes (**Figure 2**). Specifically, following the intervention, the treatment group rated the high concentration 5.6 units lower [-10.3, -1.0] than the baseline rating of 25.8 ± 3.6, while the control negligibly changed relative to baseline (baseline: 34.4 ± 2.8; change: 0.2 [-4.3, 4.7]).

<Figure 2>

Importantly, further analysis revealed that the effect of treatment group on change in umami intensity differed by sex (P-interaction=0.05). The observed difference between groups was most evident in females (P=0.013) (**Figure 3).** Rating the highest concentration of umami to at 26.3 ± 4.9 gLMS units at baseline, females rated the stimulus 8.4 units lower on the gLMS (95% CI: [-13.8, -3.1]) following exposure to MSG. Meanwhile, perceived umami intensity for females in the control group remained relatively stable (baseline mean ± SE: 35.7 ± 3.4; change: 1.3 [-3.9, 6.5]). A sensitivity analysis revealed a similar trend in those that were able better identify umami sensations at baseline via the ranking task. This relationship was not observed in males (Supplemental Table 1).

<Figure 3>

As expected, salt taste did not differ with MSG supplementation relative to the control group (effect of group: P=0.61). Presumably increasing sodium intake across groups throughout the study period, both groups tended to rate the higher salt stimuli lower on the gLMS following 4 weeks of broth consumption (Supplemental Table 1). The effect of group on salt taste did not differ by sex (P-interaction=0.98).

Umami ranking task

Both groups struggled to correctly rank umami solutions at baseline, with average scores of 2.9 ± 0.4 for the control group and 1.9 ± 0.4 for the treatment group. Although the treatment group appeared to decrease their ability to correctly rank multiple concentrations of MSG by intensity (estimated change in rank: -2.2 [-8.4, 4.1]), rank analysis of covariance controlling for baseline rank revealed no change in umami discrimination by treatment group (effect of group: P=0.35), with neither sex driving an effect (P-interaction=0.12).

Test meal intake and appetite ratings

At baseline, the amount of food eaten at the ad-libitum meal in the MSG treatment group was similar compared to the control group (463±43g versus 508±50g, P=0.50), as was the proportion of sweet and savory foods (savory: 0.75±0.03 versus 0.78±0.02; P=0.40). Following the intervention, there were group differences in the total amount eaten at the ad-libitum meal relative to baseline (P=0.04), driven primarily by differences in the savory (thus more umami-heavy) course (P=0.04) (**Figure 4**). The control group increased in consumption of savory foods relative to baseline (42g [-11, 96]), while the treatment group decreased intake (-36g [-91, 19]). This effect was also reflected in the total amount of food eaten, and did not differ by sex (P-interaction=0.15). There were negligible changes in the intake of the sweet second course (Supplemental Table 2).

<Figure 4>

Subjective appetite sensations rated throughout the ad-libitum meal were similar by treatment group at baseline (Supplemental Table 3). After the intervention, groups rated the ‘desire to eat something savory’ differently (**Figure 5**) following the savory course (P=0.04). Desire for savory foods decreased relative to baseline in the treatment group (mid-meal at baseline: 27.9 ± 4.6; change: -7.7 [-13.7, -1.7]) but not in the control group (baseline: 29.7 ± 4.6; change: 1.2 [-4.5, 7.0]), even after adjusting for the amount of food eaten at the meal.

<Figure 5>

Exploratory analysis across the sample showed a positive association between change in umami perception at lower concentrations and rated desire to eat something savory, especially after the savory course (0.76 [0.27, 1.25]; P<0.01). Changes in intake at the test meal were partially explained by changes in reported ‘desire to eat something savory’, as our data show an association between decreased ratings and decreased intake when controlling for baseline intake (2.29 [0.49, 4.08]; P=0.01). Differing palatability of the study broth did not appear to influence test meal intake following the intervention, since changes in broth liking across the study period did not correlate with the amount of savory food eaten (0.50 [-1.15, 2.15]; P=0.55).

Liking, wanting, and preferences

There were no significant effects of the intervention on the LPFQ measures. However, relative food choice (P=0.07) and implicit wanting (P=0.08) of high protein foods displayed a trend towards a significant change with treatment, but not in explicit liking (P=0.21) or explicit wanting (P=0.68) (**Figure 6**).

<Figure 6>

Hedonic evaluations for parmesan cheese, roasted almonds, pickles, and jam were generally favorable at baseline, with average ratings ranging between 17.7±4.2 and 27.0±3.2 on the hedonic gLMS for both groups, while sundried tomatoes were rated relatively neutrally (-1.0±4.0). The treatment did not change hedonic ratings for any of the real foods hypothesized to be predominantly umami (effect of group: P=0.81 for parmesan, P=0.20 for sundried tomato; P=0.62 for roasted almond), sweet (P=0.88 for jam), or salty (P=0.86 for pickles), and did not differ by sex (P-interaction=0.97 for parmesan, P-interaction=0.43 for sundried tomato, P-interaction=0.67 for almond, P-interaction=0.86 for jam, P-interaction=0.90 for pickles).

## Discussion

### Perceived umami intensity after a diet high in MSG

Our data show that repeated exposure to umami taste diminishes perceived umami intensity. However, this effect was limited to females in our study. This sex dependence may be partially explained by a lower number of males in our study. Perceived salt taste also tended to decrease across the study period, regardless of treatment group. These results are in line with previous literature suggesting that the appetitive tastes of sweet, salt, and fat may be attenuated, or preferences shifted to more intense stimuli with a diet high in the respective taste stimuli (1–3). Equivalent associations have been reported for diets low in sugar, salt, and fat (1,6,7), suggesting an adaptive relationship that is plastic with either high or low exposure to stimuli, although a diet low in umami was not assessed here.

We speculate that our results could be attributed to a down-regulation in expression of either the T1R1 or T1R3 subunit of the umami-sensing G-protein coupled receptor (43), analogous to that demonstrated for CD36 with repeated dietary exposure to fats in mice (8). In our study, sweet taste intensity (sensed by a T1R2 and T1R3 receptor heterodimer) followed a similar downward trend in those exposed to dietary glutamate compared to controls. This raises the possibility that repeated umami exposure influences the expression or function of the T1R3 subunit, since umami and sweet tastes both act partially through this receptor (43). Preliminary research in our group supports the hypothesis of decreased expression of T1Rs with long-term exposure to MSG in mice (unpublished). Similarly, earlier work revealed an association between increased consumption of umami-rich foods and impaired umami perception in a free-living human population (44).

Our results display notable sex differences, which few studies investigating tastant exposure report testing for. Sartor et al (3) found no differential sex effects on sweet taste after one month of soft drink supplementation. Regardless, sex differences are regularly observed in taste (3,11,45,46), although many studies lack an assessment of umami (10,11,47). Circulating sex hormones such as estrogen have been hypothesized to differentially influence taste perception between sexes (46), particularly during pregnancy and certain phases of the menstrual cycle (48,49). Despite this, baseline and post-treatment testing sessions were separated by 28 days, the approximate length of a typical menstrual cycle (50), limiting any effect of menstrual cycle on taste. Sex differences have been previously reported in studies of umami taste (9,44), and may modify associations between taste and BMI (9) and weight change (44). This may explain some of our results since weight was gained differentially between the sexes across the study period, although any linkage is speculative in nature.

It is possible that dietary differences between sexes could alter the effect of our intervention on taste. In line with previous accounts (51), males tended to report a higher intake of protein at baseline compared to females, as well as greater habitual glutamate consumption. However, differences in protein or glutamate intake at baseline did not explain differences in umami taste perception. Due to the small sample size of males in the treatment group (n=8), we lacked power to assess whether males differed in taste response after prolonged dietary exposure to MSG according to relative protein intake. Even so, we reason that if males regularly consume a diet higher in glutamate, any added exposure via our treatment would have less of an effect on taste compared to that observed in females. Previous reports highlighted similar phenomena, where a high fat diet had no effect on fat sensitivity in a group of individuals that were overweight, unlike a low fat diet. Another study revealed an association between habitual protein intake and reported pleasantness of MSG stimuli, but only when participants were in a state of protein deprivation (25).

Intake and desire for savory food with repeated exposure to umami taste

Our data suggests that desire for and intake of savory foods is diminished with repeated dietary exposure to MSG. There is mixed evidence detailing a link between umami taste, appetite, and satiation. In two studies, preload soups with added MSG/IMP were rated as having a stronger flavor compared to soup without additional umami stimuli, with resultant consumption of the preload with MSG decreasing subsequent intake at a test meal (13,52). It should be noted that such an effect is not consistently supported in the literature (53). While one study reported increased appetite following intake of soup with MSG (13), another reported a decrease (53), with a third reporting no influence on the motivation to eat (52). Consistently higher hedonic ratings are given to foods supplemented with umami, usually attributed to enhanced flavor (52–54), with heightened positive emotions and satisfaction also reported following consumption (54). Based on these results, we initially hypothesized that the treatment group in our study would perceive lower umami taste in the savory course than at baseline, and thus would display a diminished appetite compared to the control group, presumably due to lower perceived palatability in the test meal. However, we observed no group differences for hunger, fullness, or prospective food consumption ratings at any point in the meal in this study, and we have no data on the palatability of the meal. Alternatively, the treatment group could perceive less umami, be less satiated, and be driven to eat more compared to the treatment group. However, this was not supported in our data.  We can also rule out any demand effects on appetite due to varying liking of the two group's broths since analyses reveal no significant group differences in hedonic ratings of the broth following the 4-week treatment.

Exploratory data analyses suggest that irrespective of treatment, attenuated umami taste at lower concentrations may associate with decreased desire for savory foods.  Since females primarily decreased in perceived umami intensity with repeated exposure to MSG, whereas both sexes reported decreased desire for and intake of savory food, perceived umami intensity may not entirely explain observed behavior associated with appetite.  It is possible that intake of MSG may have postingestive appetite effects beyond the peripheral taste system, as suggested by previous literature (55,56).

Alternatively, our results could be explained with decreased intake in the test meal attributed to a diminished desire for savory food.  Indeed, this is supported in our data, where a decreased desire for savory food correlates with decreased intake in the savory course of the test meal, especially evident prior to the beginning of the meal.  Research has shown that exposure to savory has an especially strong effect on ensuing appetite and food choices (57,58).  We speculate that the treatment group may have become over-stimulated with umami taste during the treatment period and were simply less driven to consume savory, in line with sensory specific satiety theory (59).

Desire for high protein foods with a diet high in MSG

The implicit measures of liking and wanting suggested a slight increase in desire for high protein foods relative to baseline, with little change in the controls, although this did not reach the statistical threshold between groups. Those consuming the broth with MSG tended to be more likely to choose high protein foods over low in forced choice measures, and showed greater implicit wanting for high protein foods following the intervention. Assuming that umami taste simulates amino acid consumption, this result is in contrast to previous reports of increased implicit wanting for high protein foods after a low protein diet, with no change after a high protein diet (38). Alternatively, as with our study, previous results have demonstrated that decreased perception of umami associates with decreased desire for protein (12). Meanwhile, rated liking of real foods in this study did not differ with treatment, which could imply that implicit measures are more susceptible to change with exposure to umami taste than explicit measures.

Limitations and future work

Results from this study are limited to relatively young, normal-weight, non-smoking, and non-restrained eaters. Our randomized controlled study design further limits confounding factors on the outcomes. It should be noted however, that even though treatment groups in our study were randomized and balanced on sex and habitual glutamate consumption, and thus any influence of sex hormones or diet should be considered non-differential bias, it is possible that our sample was not large enough to truly limit other confounding factors. Furthermore, this study was powered to detect differences between treatment groups in perceived taste intensity, as opposed to other secondary measures. While it has been suggested that satiation and satiety can be quantified with a single ad-libitum meal (30), future studies should duplicate our findings with more than one test meal. Replication in a larger population with adjustment for multiple comparisons would also serve to remedy any concerns with testing for numerous secondary outcome measures, as well as the smaller sample size of men in our study. Although our study begins to unravel the relationship between diet, umami taste, and health, umami taste remains relatively poorly studied. Further studies examining umami taste to understand additional environmental or genetic factors that may contribute to variations in perception and food preference, and how sex may modify these relationships, would be valuable.

## Conclusion

Our results highlight a complex relationship between diet, umami taste, food preference, and appetite. Relative to controls, increased dietary exposure to MSG diminished umami taste response (selectively in females) and decreased the desire and intake of savory foods at an ad-libitum meal. Findings from this research can be applied to the study of food choice, a critical factor in the development and maintenance of diet-related diseases including obesity, osteoporosis, and kidney disease.

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**TABLES**

**Table 1.** Baseline characteristics of treatment groups[1]

| | Control (n=30) | Treatment (n=28) |
|---|---|---|
| Age (years) | 22.6 ± 4.7 | 22.9 ± 7.6 |
| Sex | | |
| Male | 8 (26.7%) | 8 (28.6%) |
| Female | 22 (73.3%) | 20 (71.4%) |
| Dietary glutamate (g/day)[2] | 13.5 ± 6.4 | 14.5 ± 9.7 |
| Protein (g/day)[2] | 68.6 ± 33.1 | 75.1 ± 54.8 |
| Race/Ethnicity | | |
| Caucasian | 19 (63.3%) | 17 (60.7%) |
| Asian/Pacific Islander | 10 (33.3%) | 6 (21.4%) |
| Other[3] | 1 (3.3%) | 5 (17.9%) |
| BMI (kg/m$^2$) | 21.3 ± 2.2* | 22.5 ± 2.2 |
| Restrained eating score (TFEQ[4]) | 6.9 ± 3.8 | 6.6 ± 2.9 |

**1** Values are mean ± SD or count (percentage of category) at baseline session

2 Assessed via Diet History Questionnaire (National Cancer Institute)

3 African American, Hispanic, and mixed races

4 Three Factor Eating Questionnaire

* Different from Control, $P < 0.05$.

**FIGURE LEGENDS**

**Figure 1.**

Flow diagram summarizing participant recruitment, screening, randomization, and study completion. [a] Did not meet inclusion criteria (n=132); Declined to participate (n=42). [b] Lost to follow-up (n=3), due to time constraints and/or failing complete study requirements (i.e. missed multiple days of broth consumption). [c] Lost to follow-up (n=4), due to time constraints and/or failing complete study requirements (i.e. missed multiple days of broth consumption); Missing data (n=1), due to failure to follow directions at testing session.

**Figure 2.**

Perceived umami (monosodium glutamate; A), sweet (sucrose; B), and salty (sodium chloride; C) taste intensity of solutions by healthy young adults following daily consumption of broth (control) or broth with MSG (treatment) for 4 wk. Values are means ± SEMs, n=30 control or 28 treatment, adjusted for baseline rating and scale usage on the generalized Labeled Magnitude Scale (gLMS). Left y-axis shows rating on gLMS, while right y-axis shows the corresponding scale descriptors on the gLMS: no sensation (NS), weak (W), moderate (M), strong (S), very strong (VS). $P \geq 0.05$ for main effect of treatment from general linear models in all tastes/concentrations.

**Figure 3.**

Change in umami taste intensity rating from baseline of healthy young men (A) and women (B) following daily consumption of vegetable broth (control) or vegetable broth with MSG (treatment) for 4 wk. Values are mean changes ± SEMs, n = 8 (both groups) for men and 22 (control) or 20 (treatment) for women, adjusted for baseline rating and scale usage and stratified by sex (P-interaction=0.05), rated on the generalized Labeled Magnitude Scale (gLMS). A positive value indicates an increase from baseline and a negative value a decrease, shown on right y-axis. P-values represent main effect of treatment from general linear models.

**Figure 4.**

Change in total, savory, and sweet food consumed from baseline in healthy young adults at ad-libitum meal consisting of pasta (savory) and ice cream (sweet) following daily consumption of broth (control) or broth with MSG (treatment) for 4 wk. Values are mean change ± SEMs in grams, n=30 (control) or 28 (treatment), adjusted for baseline amount of food eaten. A positive value indicates an increase in food eaten compared to the baseline session and a negative value a decrease, shown on the right y-axis. * $P < 0.05$ for main effect of treatment from general linear models.

**Figure 5.**

Subjective appetite sensations by healthy young adults throughout ad-libitum meal consisting of pasta (savory) and ice cream (sweet) following daily consumption of broth (control) or broth with MSG (treatment) for 4 wk, rated on visual analog scales (VAS) pre-meal, between sweet and savory courses (Mid), and post-meal. Values are means ± SEMs, n=30 (control) or 28 (treatment), adjusted for baseline session rating. Ratings were made on 100-point VAS for six dimensions of appetite: (A) hunger ('How hungry are you?'; 0=Not at all, 100=Extremely), (B) fullness ('How full are you?'; 0=Not at all, 100=Extremely), (C) satiety ('How satiated are you?'; 0=Not at all, 100=Extremely), (D) prospective consumption ('How much do you think you could eat right now?': 0=Nothing at all, 100=A very large amount), (E) desire for sweet ('How strong is your desire to eat something sweet?'; 0=Extremely low, 100=Extremely high), (F) desire for savory ('How strong is your desire to eat something savory?'; 0=Extremely low, 100=Extremely high). Left y-axis shows rating on VAS, while right y-axis shows the corresponding scale descriptors. *P-value<0.05 for main effect of treatment from general linear models.

**Figure 6.**

Change in protein appeal scores from baseline in healthy young adults following daily consumption of broth (control) or broth with MSG (treatment), assessed via the Leeds Food Preference Questionnaire. Values are mean changes ± SEMs, n=30 (control) or n=28 (treatment), adjusted for baseline score. A positive value indicates an increased wanting or liking of high protein foods from baseline and a negative value a decrease, shown on the right y-axis. P-values represent main effect of treatment from general linear models.