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Accepted Version

Wang, S., Dermiki, M., Methven, L., Kennedy, O. B. ORCID: https://orcid.org/0000-0003-3885-4872 and Cheng, Q. ORCID: https://orcid.org/0000-0001-8198-8556 (2022) Interactions of umami with the four other basic tastes in equi-intense aqueous solutions. Food Quality and Preference, 98. 104503. ISSN 0950-3293 doi: https://doi.org/10.1016/j.foodqual.2021.104503 Available at https://centaur.reading.ac.uk/102035/

To link to this article DOI: http://dx.doi.org/10.1016/j.foodqual.2021.104503

Publisher: Elsevier

Interactions of umami with the four other basic tastes in equi-intense aqueous solutions

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Highlight

- Umami taste does not enhance or suppress sweet, salty, sour or bitter in equi-intense solutions.
- Sweet, salty, sour and bitter significantly suppress umami taste in equi-intense solutions.
- Sodium chloride plus glutamate tastants maintained salty and savoury taste perception.

Key words

Umami, salty, taste, mixtures, suppression, equi-intense

Abstract

Previous research has shown that the addition of equi-intense concentrations of taste compounds leads to mixture suppression, with sweetness being the least suppressed taste while being the strongest suppressor of the other taste stimuli. However, perceived intensity of umami (savoury) within complex mixtures is less defined. Since maintaining savoury taste of foods at reduced salt levels is a growing need, this study aims to investigate the role of umami in complex taste systems. Initially the concentrations of single tastants were adjusted until a trained sensory panel rated them as equi-intense using general labelled magnitude scale (gLMS). In order to evaluate the impact of umami taste on other tastes, and vice versa, three sample sets were prepared as binary and quinary systems. The first two sets utilised monosodium glutamate (MSG) as the umami tastant; one set without balancing the sodium level in MSG (sodium unbalanced) and another set accounting for it by the addition of sodium at an equivalent molarity to all but the umami single tastant solution (sodium balanced). The third set used monopotassium L-glutamate monohydrate (MPG) as the source of umami to overcome the confounding influence of sodium. All samples were rated by trained sensory panellists. The results of the three studies conclude that umami taste does not enhance or suppress the perception of any other taste in binary aqueous taste systems ($p > 0.05$); whereas sweet, salty, sour and bitter significantly suppress the perception of umami in both binary and quinary systems ($p < 0.05$).

1. Introduction

Cross-modal interactions between two or more sensory modalities, have been investigated as a strategy for the reduction of salt and sugar (Ponzo *et al.*, 2021). For example, odour-taste interactions have been explored for the reduction of sugar (Velazquez *et al.*, 2020) and the reduction of salt (Thomas-Danguin, Guichard & Salles, 2019; Emorine *et al.*, 2021). Mojet, Heidema and Christ-Hazelho (2004) described how taste-taste interactions influenced taste in various real foods, and found that tastants evoking salty, sweet, bitter or umami could alter the perception of one or more other taste qualities in the product which they had been added to. Such taste-taste interactions can be useful in salt reduction strategies. For example, where potassium chloride (KCl) is used to replace sodium chloride (NaCl) it can increase bitterness in the final product; however, Abu et al. (2018) found that adding sweetness (via trehalose or sucrose) to a KCl/NaCl mixture effectively reduced bitterness without changing saltiness. Therefore taste-taste interactions are of relevance to the food scientist, with applications in salt and sugar reduction continuing to be a growing interest.

Psychophysical functions are used to study and express relationships between a stimulus and a response, or perceived sensation, such as taste. For individual taste stimuli, as the physical concentration increases the perceived intensity elicited by that compound also increases, but the rate of increase is not always directly proportional. It is dependent on both the specific tastant and whether the concentration is at relatively low levels (just above threshold, accelerating relationship), moderate levels (linear relationship) or high levels (decelerating relationship) (Bartoshuk, 1975; McBride, 1987).

Such stimulus response relationships are subsequently modified in tastant mixtures. In a previous review, Keast and Breslin (2002a) concluded that perception of binary taste mixtures is dependent on the position of the taste stimulus on the psychophysical curve. Whether the concentration is within the linear or decelerating (plateau) phase of the curve, helps predict whether a particular tastant would cause enhancement or suppression within a tastant mixture. In an earlier paper, McBride (1993) noted that the binary mixing of two different tastants produces three senses: an overall total intensity and a sensation from each of the two components; he suggested that the total intensity would be determined only by the strength of the stronger components.

In the case of more complex ternary and quaternary taste combinations, Bartoshuk (1975) found that tastants suppressed each other. The extent of suppression was dependent upon the function of the individual tastant; tastes where perception increased sharply with increasing concentration tended to cause greater suppression. Similarly on studying a tertiary taste mixture’s intensity of sucrose, fructose, and citric acid, McBride and Finlay (1990) found that the total perceived strength of the mixture was determined by the perceptual intensity of the individual stronger components, and the sweetness and sourness of the mixture tended to suppress each other. Taking a modelling approach to understand the psychophysics of taste interaction, Schifferstein and Frijters (1993) concluded that a summation model (addition of individual component intensities) was sufficiently able to predict total taste intensity of a mixture.

Since many foods are formulated with tastants at moderate and not extreme levels, it is likely that the influence of taste stimuli in the linear phase of the psychophysical curve might be the most relevant. The approach taken by Green *et al*. (2010) focused on taste mixtures combined at perceptually equi-intense moderate (not extreme) concentrations. They tested taste interactions in the four taste mixtures (salt, sweet, bitter and sour) using equi-intense concentrations of sodium chloride, sucrose, quinine sulfate and citric acid. Moreover, four tastes qualities in binary, ternary and quaternary mixtures were also investigated. They concluded that suppression between stimuli in binary mixtures could predict taste perception in more complex combinations. For example, the sweet taste of sucrose tended to be the least suppressed quality, whereas it was a potent suppressor to all other tastes.

Umami tastants are widely used as flavour enhancers in food products, and especially in developing salt-reduced foods. In practice such enhancement may result from complex ingredients, such as yeast extracts, that comprise both amino acids (especially glutamate) and 5′- nucleotides. However, literature often focuses on the understanding of simpler systems. A review paper by Maluly et al (2017) recommended that monosodium glutamate (MSG) could be used to reduce NaCl in a broad range of foods. In specific applications, Yamaguchi and Takahashi (1984) demonstrated that MSG could be used to reduce NaCl in a Japanese soup (Sumash-Jiru). Where MSG is used in combination with 5′-nucleotides, such as inosine-5′-monophosphate (IMP) and guanosine-5′-monophosphate (GMP), a much stronger umami taste can be achieved. Yamaguchi and Kimizuka (1979) found that the perceived umami intensity was affected by the ratio of IMP to MSG, and more recently Yamaguchi summarized that maximum taste intensity could be achieved with a 70:30 ratio of IMP to MSG (Yamaguchi, 1998). In using a combination of umami tastants, Dos et al. (2014) found that MSG, disodium inosinate, disodium guanylate could enhance flavour and maintain saltiness at 50% reduced NaCl when added into fermented cooked sausages.

However, there is limited understanding about how MSG performs in mixture of tastants, and how it interacts with other tastants, especially at equi-intense levels. Indeed, some of the findings in the literature appear contradictory which is perhaps due to the differences in levels, compounds, and test strategies applied in the sensory test. The early study by Woskow (1969), investigated the effects of umami on other tastes, but not vice versa. The study used a series of 50:50 combination of disodium 5′-inosinate and disodium 5′-guanylate from low to moderate levels (0.1mM to 0.5mM), while MSG was not included. This umami combination was found to enhance sweetness and saltiness but suppress sourness and bitterness. Reporting on work from their laboratory in 1979, Yamaguchi (1998) noted that MSG slightly enhanced saltiness from NaCl, but only at high MSG concentrations, and found that NaCl had no substantial influence on the perception of umami, while all other tastes did suppress umami. Kemp and Beauchamp (1994) demonstrated that at threshold levels, MSG had no influence on sweet, salt, sour and bitter, while at supra-threshold concentrations it suppressed sweet and bitter tastes and enhanced salt perception.

The findings of Kemp and Beauchamp (1994) for bitterness suppression corroborates the work of Woskow (1969), which is perhaps unsurprising as the levels of bitter tastant, quinine sulfate, were relatively similar (0.007 and 0.025 mM respectively) in the two studies and the perceived intensity of MSG at the medium level was similar to the recorded umami intensity of the two ribonucleotides in the earlier study. However, for saltiness, Woskow (1969) concluded that ribonucleotides enhanced salty taste at moderate concentration ($\geq$ 0.2mM), whereas Kemp and Beauchamp (1994) reported the enhancement of umami taste on salty taste only happened at high concentration of MSG (0.032mM and 0.059mM), as also concluded by Yamaguchi (1998). In relation to sweet taste, the conflicting result is likely to be due to the difference in sucrose levels used between the two studies. Sweetness was enhanced when the sucrose levels was 5% (w/v) or 0.16 M (Woskow, 1969), whereas it was suppressed when the level was three times lower at 0.05 M (Kemp & Beauchamp, 1994).

Bitterness suppression was later confirmed by Keast and Breslin (2002b), concluding that when using either MSG or adenosine monophosphate sodium salt (NaAMP), the bitter taste of any of five different bitter tastants was suppressed. However, according to the research by Fuke and Ueda (1996), NaAMP does not evoke umami taste alone, hence, inferring that taste suppression may not require the suppressing tastant to be perceived. Bitter and umami tastes are mediated via G-protein-coupled receptors, T1Rs and T2Rs which are found in type II taste receptor cells (Bachmanov & Beauchamp, 2007). Kim *et al.* (2015) established that the suppression of bitter taste by umami could occur at a cellular level, by investigating umami-bitter taste interactions with a cell-based assay using hTAS2R16-expressing cells. They tested the effect of five umami peptides (Glu-Asp, Glu-Glu, Glu-Ser, Asp-Glu-Ser, and Glu-Gly-Ser) on the bitter tastant salicin and found that the glutamayl peptides inhibited the salicin-induced intracellular Ca^{2+} response. Specifically, the Glu-Glu peptide suppressed salicin-induced activation of hTAS2R16 to a greater extent compared with the probenecid, a specific antagonist of hTAS2R16.

Previous studies have considered taste-taste interactions within ternary and quaternary mixtures (Bartoshuk, 1975; Breslin & Beauchamp, 1997; Green *et al.*, 2010). Breslin and Beauchamp (1997) investigated the interaction between sweet, salt and bitter, and found that bitter (urea) and sweet (sucrose) suppressed each other when mixed together. However, when salt (sodium acetate) was added the bitterness substantially decreased and the sweetness increased. While these papers focused on complex tastant mixtures, umami tastants were not included, and there are few studies exploring the specific interaction between umami and saltiness along with other basic tastes i.e., sweet, bitter and sour. Therefore, in order to study the effect of umami on the perception of other taste stimuli and vice versa, aqueous model systems were established to assess the taste perception using equi-intense taste mixture combinations, where the intensity levels are realistic to levels typically present in foods. Progressing understanding from previous literature this study specifically hypothesised that at moderate levels of umami sensation, saltiness would not be enhanced but neither would saltiness suppress umami, anticipating therefore by the summation model that the overall taste perception of a savoury system would be increased.

2. Materials and Methods

2.1 Panelists

A total of 12 trained sensory panelists (11 females and 1 male, age 35 to 65) participated in all experiments. They were also screened for their detection, discrimination and description ability. All panelists were healthy and had no taste or olfactory defects or disorders. They were all employed as sensory panelists and provided consent through their employment to taste foods and for their data to be used.

2.2 Stimulus

The taste stimuli used (indicated in Table 1) were aqueous solutions of sucrose (granulated sugar, Co-op Food, Manchester, UK) for the taste quality sweet (S), sodium chloride (table salt, Co-op Food, Manchester, UK) for salty (N), citric acid (Sigma-Aldrich, Gillingham, UK) for sour (C), quinine hemisulfate salt monohydrate (Sigma-Aldrich, Gillingham, UK) for bitter (Q), monosodium glutamate MSG and monopotassium L-glutamate monohydrate (MPG) (Ajinomoto, Paris, France) for the taste quality umami (U). Each tastant solution was prepared in mineral water (Harrogate Spa, UK) a day before the panel session and kept in the fridge (4 °C) overnight. All tastant solutions were taken out of the fridge prior to the test to equilibrate to ambient temperature, then 15 mL of the sample was poured into 20 mL transparent polystyrene cups labeled with three-digit random codes and were served to the panel at ambient temperature (22 ± 2 °C).

2.3 Training

Prior to the data collection, all panelists participated in training on the use of the general labelled magnitude scale (gLMS). Compared to labelled magnitude scale (LMS) first developed by Green, Shafer, and Gilmore, (1993), the top of gLMS is defined as "strongest imaginable of any sensation", which is more suitable for this experiment where intensity across modalities is compared (Bartoshuk *et al.*, 2004). The descriptors of the magnitude estimates were "barely detectable", "weak", "moderate", "strong", "very strong" and "strongest imaginable of any sensation" (anchored values on gLMS scale 0.14, 0.76, 1.12, 1.52, 1.70, 1.98; exponentiated values 1.38, 5.01, 15.9, 31.6, 50.1 and 95 respectively) (Bartoshuk *et al.*, 2004).

During the training period, panelists were asked to rate the taste intensity of the five basic taste stimuli respectively. The concentration of each stimulus used in this experiment was finalized when each stimulus was perceived as equi-intense (within the range from 'strong' to 'very strong' sensation on gLMS) by the panel. The training for finalizing the choice of concentration for stimuli was completed in three days.

2.4 Tastants preparation

Each of the three experiments described below in detail, contained a total of 10 tastants, including five single tastant solutions and five tastant mixtures (four binary, one quinary). All 12 panelists took part in all three experiments. After the training session, the first set of solutions (Experiment 1) using MSG as the source of umami with sodium unbalanced (UB) was scored by the panel, which were followed by solutions using MSG as the source for umami with sodium balanced (B) (Experiment 2). Finally, the panel was required to taste the third set of solutions (Experiment 3) which were prepared using MPG as the source for umami. For the three experiments, scoring for the samples were completed within two days.

2.4.1 Experiment 1:MSG as the source of umami with sodium unbalanced (UB)

Based on the training results to determine equi-intensity, the single stimulus was selected at concentrations with the mean panel scores being between strong and very strong on the gLMS. The concentration of each tastant was kept constant in each binary and quinary tastant mixture as seen in Table 1.

2.4.2 Experiment 2: MSG as the source for umami with sodium balanced (B)

NaCl contains 39.34% (w/w) sodium whereas MSG contains 13.6% (w/w) sodium. Therefore, an experiment was designed to ensure that sodium levels were controlled so that a raised sodium level in samples were perceived as salty taste. To achieve this, 0.015 M NaCl was added to all single tastants except MSG (Table 1). Based on the training results to determine equi-intensity, the single stimulus was selected at concentrations with the mean panel scores being between strong and very strong on the gLMS. The concentration of each tastant was kept constant in each binary and quinary tastant mixture as seen in Table 1.

2.4.3 Experiment 3: MPG as the source for umami

In order to remove the possible influence of sodium in glutamate when evaluating saltiness, the source for the taste quality of umami was changed to MPG. The concentration of each tastant was also adjusted to achieve a slightly lower equi-intensity

Table 1: Concentration of tastants used in binary and quinary mixture sets

Sample*	Experiment 1: Concentration used in MSG (sodium unbalanced) set MSG (UB)	Experiment 2: Concentration used in MSG (sodium balanced) set MSG (B)	Experiment 3: Concentration used in MPG set
S	S 0.19 M	S 0.19 M + N 0.015M	S 0.10 M
N	N 0.08 M	N 0.08 M + N 0.015M	N 0.05 M
C	C 0.005 M	C 0.005 M + N 0.015M	C 0.004 M
Q	Q 0.025 mM	Q 0.025mM + N 0.015M	Q 0.02 mM
U	U 0.015 M	U 0.015M	U 0.01 M
U+S	S 0.19M, U 0.015M	S 0.19M, U 0.015M	S 0.10M, U 0.01M
U+N	N 0.08M, U 0.015M	N 0.08M, U 0.015M	N 0.05M, U 0.01M
U+C	C 0.005 M, U 0.015M	C 0.005 M, U 0.015M	C 0.004 M, U 0.01M
U+Q	Q 0.025mM, U 0.015M	Q 0.025mM, U 0.015M	Q 0.02mM, U 0.01M
U+S+N+C+Q	S 0.19M, N 0.08M, C 0.005 M, Q 0.025mM, U 0.015M	S 0.19M, N 0.08M, C 0.005 M, Q 0.025mM, U 0.015M	S 0.10M, N 0.05M, C 0.004 M, Q 0.02mM, U 0.01M

[*] S = sucrose; N = sodium chloride; C = citric acid; Q = quinine hemisulfate salt monohydrate; U = monosodium glutamate (MSG) or potassium L-glutamate monohydrate (MPG)

on the gLMS between the descriptors moderate and strong, which allows a liner relationship between stimuli and response on the psychophysical curve as the one achieved in experiments 1 and 2 (Table 1).

2.5 Sensory evaluation

The experiments were conducted within a standard sensory environment using individual sensory booths, artificial daylight and controlled room temperature (22 ± 2 °C). All samples were blind-coded and presented monadically. During tasting sessions, panelists were instructed to sip and hold the stimulus in their mouths for five seconds before swallowing and rating six attributes for each sample as follows: overall taste intensity, sweet, salty, sour, bitter and umami intensity. Between samples, the panel was instructed to cleanse their palate with plain crackers and water (filtered tap water at room temperature) to return the mouth back to a neutral state; an automatic reminder appeared during the countdown of ninety seconds between each stimulus after evaluating consecutive taste samples. Within each experiment scoring sessions included 10 samples and 2 replicates scored across two days. Sample presentation order was balanced across panelists; they each received different sample orders between each other, between replicates and between experiments. Data were captured using the sensory software Compusense® (cloud version, Guelph, Ontario).

2.6 Data analysis

Data from each of the three experiments was analysed separately. Log data from each panelist from the gLMS were captured by Compusense®. Data were exponentiated. Two-way analysis of variance (ANOVA) was carried out using Senpaq (QI Statistics, Reading, UK) where panelists were treated as random effects and samples as fixed effects, main effects were tested against the assessor by sample interaction. Multiple pairwise comparisons were carried out using Tukey’s HSD at a significance level of 0.05.

3. Results

The mean scores of perceived taste intensity for all single tastes and taste mixtures are given in Figures 1 to 3 (further statistical details given in supplementary Table 1 to 3). The aim was to have all single tastants rated “strong to very strong” on the gLMS (1.52 to 1.70 on the log scale, or 31.6 to 50.1 exponentiated values) in both the sodium unbalanced and balanced sets. Although panelists were extensively trained on each single tastant, saltiness and sourness were rated slightly lower than “strong”. However, the mean ratings (exponentiated data) only fell below this descriptor by a maximum of 0.4 units, therefore it is suggested that this would not have greatly influenced the results. For samples using MPG as source of umami taste, all single tastants were rated as “moderate to strong” on the gLMS (1.21 to 1.52 on the log scale, or 15.85 to 31.62 as exponentiated values), while the concentration of tastants used was slightly lower in comparison to the MSG set samples.

3.1 Intensity of umami

The ratings of perceived intensity of umami in the different experiments are presented in Figure 1. It is clear from this figure that the perception of umami was significantly suppressed by all other tastes in both the binary and quinary mixtures. In all experiment sets, all the taste mixtures containing MSG were significantly ($p < 0.05$) lower in perceived umami intensity compared to MSG alone (U). The umami sensation was reduced from just above “strong” to “moderate” or “weak” in virtually all cases. The main exceptions were where the binary mixture was with sodium chloride (U+ N), this led to a lower reduction in umami, leading to “moderate” sensation rather than “weak”. The intensity of umami in the quinary taste systems (U+S+N+C+Q) was the lowest for all experiment sets.

3.2 Intensity of other tastes

The ratings of perceived intensity of sweetness, saltiness, sourness and bitterness can be seen in Figure 2. The umami taste did not enhance or suppress the perceived intensity of any other taste in the binary taste systems ($p > 0.05$) (further statistical details given in supplementary Table 1 to 3). This is an unusual phenomenon as all other taste modalities will suppress each other when added together (Green *et al.*, 2010), and yet the addition of MSG as an umami tastant has neither suppressed, nor enhanced, perception of the other four tastes. Kemp and Beauchamp (1994) concluded that MSG at medium concentration (0.032M) suppressed sweet and bitter tastes and at higher concentrations (0.059M) enhanced salty taste. The MSG levels used by Kemp and Beauchamp (1994) are higher than the 0.015M used in the current study which may have partly led to the different findings. However, the main reason is likely to be the different concentration of the other tastants. The present study used 0.19 M sucrose and 0.005 M citric acid for equi-intense perception of "strong to very strong".

3.3 Overall taste intensity

The ratings of perceived intensity of overall taste in the different experiments are presented in Figure 3. Results indicated that the total taste intensity of binary mixtures was very similar to the total overall taste intensity of single tastants ($p > 0.05$), except for quinine hemisulfate with umami mixture (U+Q) in the sodium balanced set and sodium chloride with umami mixture (U+N) in MPG set, where the binary mixture was significantly higher in overall taste intensity ($P<0.05$). The total taste intensity of the quinary solution had a higher mean rating than all binary mixtures. In particular, it had a significantly higher rating compared to the binary mixture with citric acid (U+C) in both MSG sessions, and the binary mixture with sodium chloride (U+N) in sodium balanced set and MPG set ($p < 0.05$). The perception of all five tastes were all significantly and substantially lower in the quinary mixtures than as single tastants ($p < 0.05$) in the sodium balanced set and MPG set. In the sodium unbalanced set, sour, bitter and umami tastes were similarly significantly lower in the quinary mixtures than as single tastants ($p < 0.05$).

The binary mixture with quinine hemisulfate (U+Q) had a significantly higher overall taste intensity than the sample of quinine hemisulfate alone (Q) only in sodium balanced set ($p < 0.05$), but not in sodium unbalanced set and MPG set. This could possibly be due to the inclusion of 0.015mM NaCl in quinine solution in the sodium balanced set. Keast and Breslin (2002a) reported that NaCl has suppression effect on the bitterness perception at low, medium and high intensity level. Therefore, 0.015M salt addition would lead to a lower intensity of bitterness for quinine solution in sodium balanced set (Experiment 2), while it is not the case in sodium unbalanced set (Experiment 1) and MPG set (Experiment 3). As the total overall intensity is determined by the dominant taste (bitterness), as a result, a low overall taste intensity in quinine hemisulfate alone solution (Q) was expected compared with that in quinine hemisulfate with umami mixture (U+Q) in sodium balanced set. The binary mixture of MPG and NaCl (U+N) had a significantly higher overall taste intensity than the sample of NaCl (N) alone ($p < 0.05$). This indicates that umami may enhance the total intensity of a salt solution without enhancing the specific taste modality (saltiness) in the MPG mixture. The binary mixtures of U+N in the MSG sample set had a similar trend, but the differences were not significant ($p > 0.05$). These differences may be associated with the difference in concentrations used in the MSG and MPG sets (0.08M or 0.095M vs 0.05M). Finally, the total taste intensity of the quinary solution was the strongest, with all single tastants having a significantly and substantially lower overall taste intensity than the quinary mixtures except quinine hemisulfate ($p < 0.05$).

3.4 Taste interaction

The testing of the balanced sodium sample set allowed for an unbiased investigation of the influence of glutamate and the perception of all other tastes, and of the effect of sodium on glutamate, without the sodium within the MSG as a confounding factor. In conclusion, the results from both the sodium unbalanced and balanced trials were the same, increasing the confidence in the overall finding that umami from glutamate does not enhance or suppress other tastes when all tastes are presented at strong (but not excessive) intensity levels. The findings in this MPG set again confirmed that all other tastes suppressed umami ($p < 0.05$), whereby all binary mixtures had significantly lower umami intensity than MPG alone ($p < 0.05$), and the quinary mixture was significantly and very substantially lower in umami taste ($p < 0.05$). The results agree with the first two studies that the umami taste did not enhance or suppress the perceived intensity of any other taste in the binary taste systems ($p > 0.05$), all other tastes could suppress the perception of umami taste in binary and quinary mixture ($p < 0.05$).

4. Discussion

Figure 4 summarizes the overall findings which were common to all three studies presented in this paper, illustrating the associations between umami and the other four basic tastes. As seen in this figure the addition of umami taste did not enhance or suppress any other taste, however, the addition of sweet, salty, sour and bitter do significantly suppress the umami taste.

Keast and Breslin (2002a) have shown that the concentration of taste stimuli, and the position on the concentration-intensity psychophysical curve could predict the interactions of tastes in taste mixtures. In the current study however, no matter whether it was in the “moderate” perceived intensity region or in “strong” perceived intensity region, the umami taste did not enhance or suppress the perceived intensity of any other taste in the binary taste systems; where sweet, salty, sour and bitter all significantly suppressed the perception of umami intensity in the binary and quinary taste systems. Previous research has tended to agree that umami enhances salt perception in aqueous solutions (Woskow, 1969; Kemp & Beauchamp, 1994) and in foods (Dermiki *et al.*, 2013; Kremer *et al.*, 2013; Khetra *et al.*, 2019), and in recent years food manufacturers have been keen to use umami to enhance salty taste. However, the experimental results from this study conclude that umami taste did not affect the salty taste when presented at moderate or strong equi-intensities.

The disagreement between the current study and previous findings may be explained by the following factors: First, the levels of tastants used varies between studies. Compared to studies that previously used MSG, the 0.015M used in this study was lower than the levels found in the Kemp and Beauchamp study (1994) to enhance salty taste (0.032 and 0.059M MSG), and the level of sodium chloride used in the previous study was much lower (0.025M compared to 0.08M in the present study).

In addition, test procedure differences, i.e. a taste and spit procedure vs a taste and swallow procedure, are also responsible for the conflict. Running and Hayes (2017) have previously concluded that taste ratings resulting from model solutions that had been spat out are lower than ratings for swallowed samples on a gLMS scale. Taken together these arguments might infer that umami may enhance salty perception where salty taste is lower. Kawasaki *et al.* (2016) give an insight into the time over which the different tastes are perceived, for example saltiness and sourness tend to be perceived as dominant before swallowing, whereas umami was dominant after swallowing. This finding highlights the effect of the test methodology on the perceived intensity of taste. The sip and spit method was used by Kemp and Beauchamp (1994), while Keast and Breslin (2002b) did not include swallowing. But solutions were swallowed in the present study. Therefore, it is difficult to compare the results of studies where the tests were not conducted in the same way. Kawasaki *et al.* (2016) also investigated the duration of impact of taste attributes of umami (MSG), salty (sodium chloride), sour (lactic acid) and their binary mixtures using temporal dominance of sensations methodology. They found that the presence of MSG increased the duration of NaCl saltiness but suppressed the sourness of lactic acid. On the other hand, the duration of umami taste of MSG was suppressed in the presence of NaCl but was not affected by lactic acid. This means that MSG could increase the duration of salty taste from NaCl rather than enhance the peak intensity. This might imply that where previous studies have reported an enhancement of salty taste, it could have been that the taste duration was extended rather than an increase in maximum intensity. However, our study was specifically set up to test maximum intensity following the sample remaining in the mouth for 5s, and so would not have captured an increase in duration that the Kawasaki study concluded.

A second explanation for such discrepancies might be that umami is a less recognised taste in Western countries and consumers may perhaps confuse it with salty perception, despite it being one of the five basic tastes (Cecchini *et al.*, 2019). Although the panelists in this study were trained to recognise and score umami taste, they were UK assessors and as such they would not be habituated to umami taste throughout their lives, which might have affected their scoring. Certainly, in previous studies where functional magnetic resonance imaging (fMRI) was employed, it was confirmed that there was only a slight difference between the positions of the activation regions between umami and salty taste, which led to the conclusion that the basic perception system of umami taste was very similar to the basic perception system of salty taste (Nakamura *et al.*, 2011). Furthermore, Onuma, Maruyama, and Sakai (2018) had reported that the NaCl solutions with MSG increased responses in the frontal operculum but did not affect the hemodynamic salivary by functional near-infrared spectroscopy (fNIRS) data. This means that the umami induced saltiness enhancement effects occur in the central gustatory processing in the brain. Additionally, this might partly explain why umami, in the MPG model, was found to enhance the total taste intensity of the salt solution, without enhancing the specific taste modality (saltiness).

The type of panelist used in different studies should also be considered. Trained sensory panelists, such as the assessors in this study, “dissect” a product into its component attributes for rating, whereas consumers “synthesise” the information from the foods they are tasting (Ares & Varela, 2017). Compared with untrained consumers, trained panelists are more sensitive to taste discrimination, and they are significantly more aware of the flavour in the mixture and the intensity of suppression (McBride & Finlay, 1989; Prescott, Ripandelli & Wakeling, 2001), although their hedonic perception of the product may not fully represent the wide and varied perceptions from untrained consumers (Ares & Varela, 2017). So, one might expect a consumer would synthesise congruent taste information in a way that a trained panelist might not, leading more readily to the conclusion that a salt reduced food that is higher in umami might have an overall similar salty perception as the two tastes are congruent. However, the previous studies which concluded that umami enhanced salty taste perception were all carried out with trained panelists (Woskow, 1969; Kemp & Beauchamp, 1994; Keast &

Breslin, 2002b), as employed in the current study; so, the differences in perception between trained panellists and consumers, does not lead to a satisfactory explanation of conflicting results.

When Green *et al.* (2010) studied binary, ternary and quaternary mixtures, they found that the overall perceived intensity of the mixtures was best predicted by perceptual additivity, the sum of the tastes perceived within the mixture (Green *et al.*, 2010). In fact, their study concluded the sum of the unmixed taste intensities to be much higher than the sum of the taste intensities in the mixture, or the overall taste intensity ratings, thus ruling out stimulus additivity (Keast & Breslin, 2002a). In the current study, it was consistent that the overall taste intensity was lower than both the sum of the unmixed taste intensities and the sum of the taste intensities in binary system and quinary mixture. However, it was relatively easy to distinguish each taste in the binary system but much more difficult to distinguish each taste in the quinary mixture system, which may lead to a great reduction in intensity compared to a single tastant.

One limitation of this work was that when the source of umami was changed from MSG to MPG, the concentration level did not remain in the same taste intensity level. It means the relationship between the five basic tastes is only valid at certain taste intensity level and for certain umami compound, i.e. from moderate to strong when MPG was used as the source of umami; from strong to very strong when MSG was used as the source of umami. Even if the results presented same trend (suppression), the impact of concentration range on perception was uncertain. However, it provides a prediction for the relationship of the five basic tastes when MSG is used as the source of umami at other concentration levels in the future.

In fact, taste interactions in a real food matrix are more complicated compared to aqueous solutions. This can explain why for example, MSG is added in variety of food products (e.g., soup, potato chips, sausage) to replace NaCl as well as to enhance flavour (Yamaguchi & Takahashi, 1984; Dos *et al.*, 2014; Maluly *et al.*, 2017). However, increasing saltiness perception using MSG in the aqueous model system of the current study was not observed. The discrepancy could be explained due to the complexity of food matrices which affects the perception. In a real food there are cross-modal interactions between two or more sensory modalities such as taste-flavour or flavour-texture interactions. Additionally, ingredients used in food products are often added at much higher concentrations than in the aqueous model systems to achieve the required taste intensity, considering that the texture can reduce intensity. In general, meat products have a high sodium content, and the salt content is around 2% (Inguglia *et al.*, 2017), where only 0.29% or 0.55% salt was used in this study. Other research used higher MSG levels, 0.38% MSG was added to the sumashi-jiru (soup) to maintain the salty taste, and 0.3% MSG added to the sausage to compensate the saltiness loss caused by 50% salt reduction in low-sodium fish burgers (Quadros *et al*., 2015). In contrast, only 0.19% or 0.25% MSG was used in this study. Therefore, the conclusions reached by investigating aqueous model solution may not be applicable to food systems directly, however they offer the basis for the design of further experiments in real foods.

The present study employed a trained sensory panel to investigate taste interactions, with limited variability in taste sensitivities. Prescott *et al.* (2001) concluded that perception of tastes and interaction between tastes in binary mixture are affected by the 6-n-propylthiouracil (PROP) taster status, i.e. supertaster, medium taster and non-taster. However, the taste sensitivity is determined by many factors, such as genetic differences in taste receptors, including Tas2R38 gene that is predominantly responsible for PROP/PTC (phenylthiocarbamide) tasting (Hayes *et al,* 2008), and single nucleotide polymorphisms (SNPs) for epithelial sodium channel (ENaC) (Chamoun *et al*, 2021). For example, SNPs for the T1R receptors influence perception of sweet and umami taste. Therefore, to truly understand the influence of umami taste in taste mixtures for all consumers, a study considering taste sensitivities to basics tastes (each from more than one tastant) alongside genotyping would be needed in a large population cohort in the future.

5. Conclusions

The aim of this study was to investigate taste interactions in mixtures containing umami in the form of MSG and MPG. The result shows that the addition of umami taste did not enhance or suppress any other taste. Therefore, umami is dissimilar to other tastants which tend to suppress one another. However, the addition of sweet, salty, sour and bitter do significantly suppress the umami taste. The findings of this study are significant because they fill the gap that existed in the literature considering the effect of umami taste in taste mixture interactions and have an impact on our understanding of the underlying mechanisms of taste interactions that can be applied in food reformulation. Although umami was not found to enhance salty perception, as hypothesised, neither did it suppress it; hence when used together sodium chloride plus glutamate tastants maintained salty perception in addition to savoury taste perception, irrespective of the glutamate salt used. Overall, there is little evidence on the effect of umami on other taste stimuli, and the findings of the current study are difficult to compare directly with the limited information currently available in the literature. The reasons for this are the different sensory tests used (ranking vs gLMS), the different methodology (sip and spit vs swallowing), the different concentrations of tastants and the difference in perception of similar concentrations by the different groups studied. Further investigation is needed to determine whether these findings in aqueous solutions apply to real food systems where more complex and cross-modal interactions take place.

Acknowledgement

The sensory panelists are thanked for attending the sensory evaluation sessions Compusense are thanked for their provision of Compusense cloud software under their academic consortium agreement.

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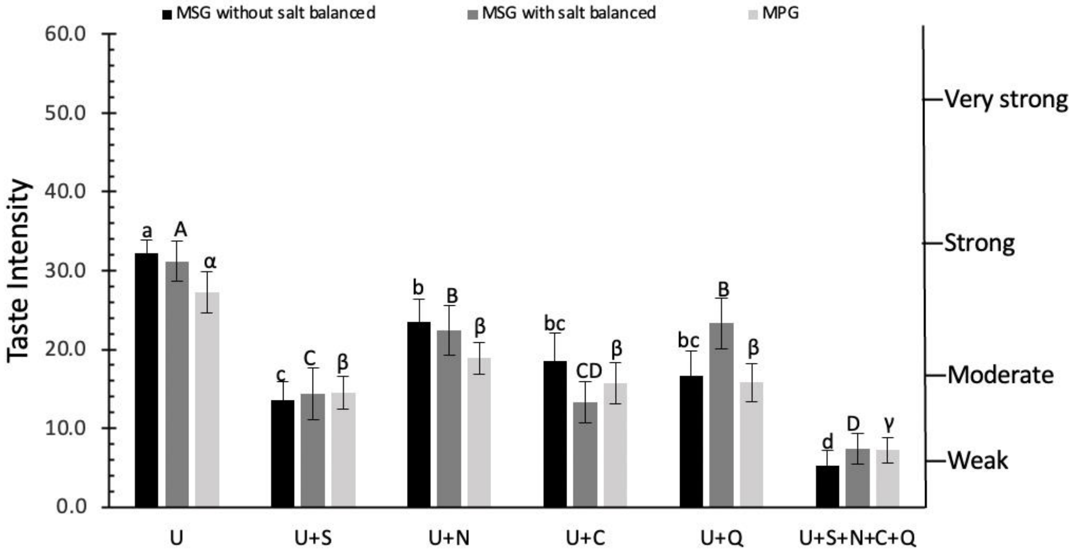

Figure 1. Ratings of perceived intensity (exponentiated values) of umami in the sodium unbalanced and balanced sets and using MPG as source of umami taste set. S = sucrose; N = sodium chloride; C = citric acid; Q = quinine hemisulfate salt monohydrate; U = monosodium glutamate (MSG) or potassium L-glutamate monohydrate (MPG). Within each sample set bars that do not share a common letter denote samples that differed significantly ($p < 0.05$). Lower case letters used for Experiment 1:MSG without salt balanced, upper case letters used for Experiment 2: MGS with salt balanced, and Greek letters used for Experiment 3: MPG.

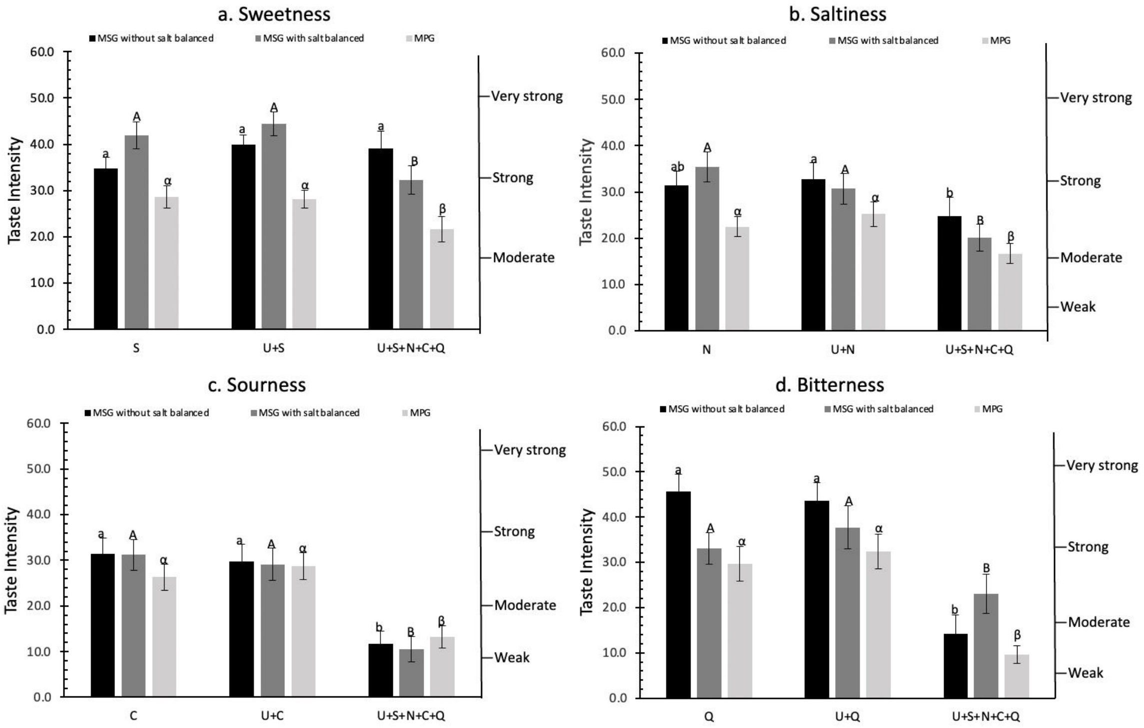

Figure 2. Ratings of perceived intensity (exponentiated values) of sweetness (a), saltiness (b), sourness (c), and bitterness (d) in the sodium unbalanced and balanced sets and using MPG as source of umami taste set. S = sucrose; N = sodium chloride; C = citric acid; Q = quinine hemisulfate salt monohydrate; U = monosodium glutamate (MSG) or potassium L-glutamate monohydrate (MPG). Within each sample set bars that do not share a common letter denote samples that differed significantly ($p < 0.05$). Lower case letters use for Experiment 1:MSG without salt balanced, upper case letters use for Experiment 2: MGS with salt balanced, and Greek letters use for Experiment 3: MPG.

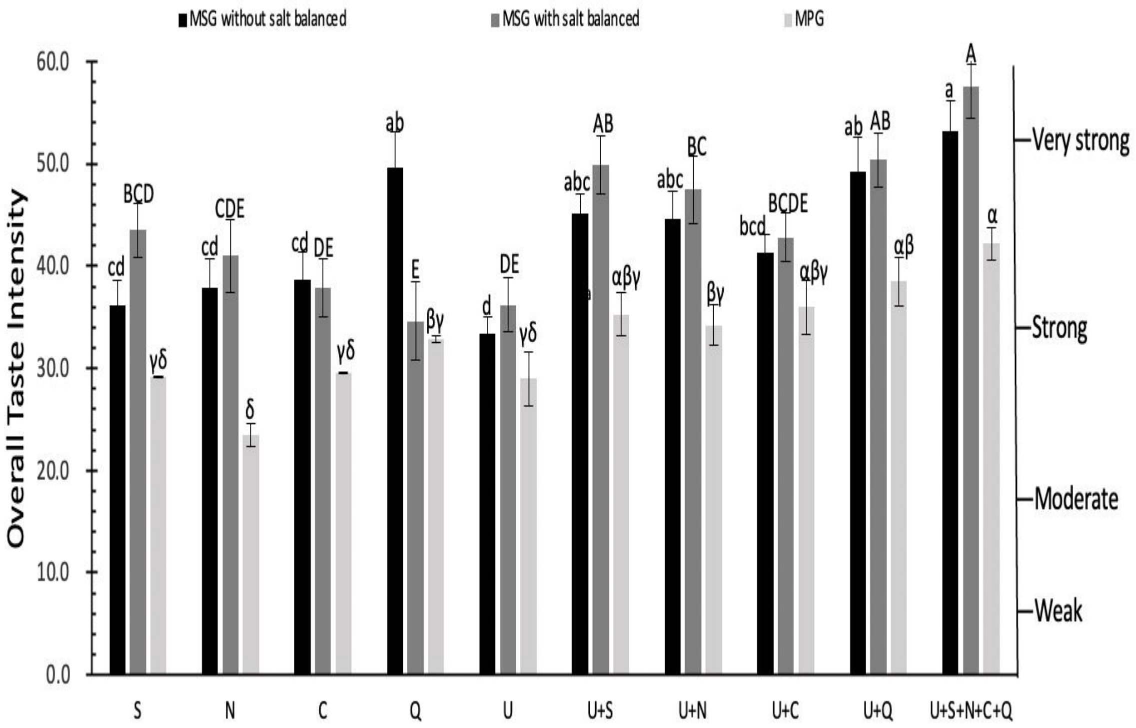

Figure 3. Ratings of perceived intensity (exponentiated values) of overall taste in the sodium unbalanced and balanced sets and using MPG as source of umami taste set. S = sucrose; N = sodium chloride; C = citric acid; Q = quinine hemisulfate salt monohydrate; U = monosodium glutamate (MSG) or potassium L-glutamate monohydrate (MPG). Within each sample set bars that do not share a common letter denote samples that differed significantly ($p < 0.05$). Lower case letters use for Experiment 1:MSG without salt balanced, upper case letters use for Experiment 2: MGS with salt balanced, and Greek letters use for Experiment 3: MPG.

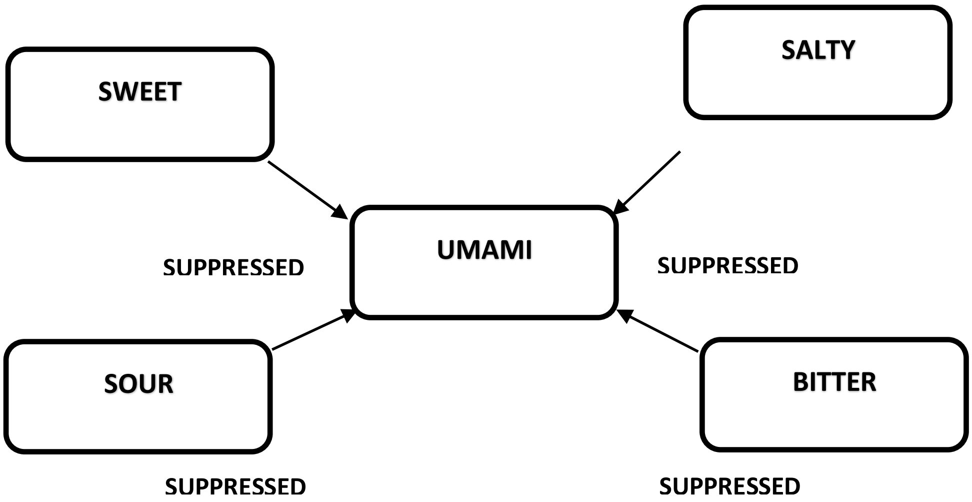

Figure 4. Binary interactions of taste qualities at equi-intense concentrations. Direction of the arrow indicates the significant influence of primary taste on umami ($p<0.05$). It may be noted that there is no effect of umami on the primary tastes including sweet, salty, sour and bitter.

Supplementary Table 1 for Experiment 1. Ratings and significance testing (ANOVA) results of perceived intensity (antilogged values) of overall taste, sweet, salty, sour, bitter and umami where MSG was used as the umami tastant without sodium balance.

	Perceived intensity (mean of antilogged gLMS intensity ratings)					
Sample	Total intensity	Sweet	Salty	Sour	Bitter	Umami
S	36.2^{cd}	34.7^{a}	2.5^{c}	2.2^{c}	1.9^{c}	1.2^{d}
U+S	45.1^{abc}	39.9^{a}	6.3^{c}	1.6^{c}	1.9^{c}	13.5^{c}
N	37.9^{cd}	1.1^{b}	31.4^{ab}	1.1^{c}	4.1^{c}	2.8^{d}
U+N	44.6^{abc}	4.5^{b}	32.8^{a}	1.3^{c}	2.5^{c}	23.5^{b}
C	38.7^{cd}	1.4^{b}	3.6^{c}	31.4^{a}	9.3^{c}	1.0^{d}
U+C	41.3^{bcd}	2.2^{b}	5.0^{c}	29.8^{a}	8.3^{c}	18.5^{bc}
Q	49.6^{ab}	1.0^{b}	1.1^{c}	1.9^{c}	45.6^{a}	1.0^{d}
U+Q	49.2^{ab}	1.1^{b}	2.7^{c}	1.4^{c}	43.6^{a}	16.6^{bc}
U	33.4^{d}	1.4^{b}	5.6^{c}	1.1^{c}	1.5^{c}	32.2^{a}
U+S+N+C+Q	53.2^{a}	39.1^{a}	24.7^{b}	11.7^{b}	14.2^{b}	5.3^{d}
df of Sample	9	9	9	9	9	9
df of Interaction	72	72	72	72	72	72
F-value of Sample Effect	4.08	80.81	24.8	29.93	25.45	19.22
Sample significance (p)	0.0003	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

^{abcde} Values within a column which don't share a common superscript are significantly different in means ratings of the perceived magnitude from Tukey's HSD test at the 95% confidence interval. S = sucrose; N = sodium chloride; C = citric acid; Q = quinine hemisulfate salt monohydrate; U = monosodium glutamate (MSG). *df* = degrees of freedom of interaction, noting that the main effect of sample (F-value of sample) was determined by dividing the variance of sample by the variance of the interaction (MSsample/MSinteraction) hence both the *df* of sample and interaction are given.

Supplementary Table 2 for Experiment 2. Ratings and significance testing (ANOVA) results of perceived intensity (antilogged values) of overall taste, sweet, salty, sour, bitter and umami where MSG was used as the umami tastant with sodium balance.

	Perceived intensity (mean of antilogged gLMS intensity ratings)					
Sample	Total intensity	Sweet	Salty	Sour	Bitter	Umami
S	43.5^{bcd}	41.9^{a}	4.9^{c}	1.2^{c}	1.1^{c}	1.0^{e}
U+S	49.9^{ab}	44.4^{a}	5.3^{c}	2.2^{c}	1.6^{c}	14.4^{c}
N	41.0^{cde}	2.1^{c}	35.4^{a}	2.8^{c}	3.0^{c}	6.2^{e}
U+N	47.5^{bc}	2.4^{c}	30.7^{a}	2.8^{c}	3.0^{c}	22.4^{b}
C	37.9^{de}	2.0^{c}	5.0^{c}	31.2^{a}	6.0^{c}	1.3^{e}
U+C	42.8^{bcde}	1.7^{c}	7.4^{c}	29.1^{a}	6.7^{c}	13.3^{cd}
Q	34.6^{e}	1.4^{c}	5.2^{c}	2.5^{c}	33.0^{a}	1.5^{e}
U+Q	50.4^{ab}	1.4^{c}	8.3^{c}	1.5^{c}	37.7^{a}	23.3^{b}
U	36.2^{de}	1.9^{c}	8.1^{c}	2.8^{c}	1.5^{c}	31.2^{a}
U+S+N+C+Q	57.5^{a}	32.3^{b}	20.1^{b}	10.5^{b}	23.1^{b}	7.4^{de}
df of Sample	9	9	9	9	9	9
df of Interaction	90	90	90	90	90	90
F-value of Sample Effect	2.64	113.66	23.5	28.39	21.03	21.16
Sample significance (p)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

^{abcde} Values within a column which don't share a common superscript are significantly different in means ratings of the perceived magnitude from Tukey's HSD test at the 95% confidence interval. S = sucrose; N = sodium chloride; C = citric acid; Q = quinine hemisulfate salt monohydrate; U = monosodium glutamate (MSG). *df* = degrees of freedom of interaction, noting that the main effect of sample (F-value of sample) was determined by dividing the variance of sample by the variance of the interaction (MSsample/MSinteraction) hence both the *df* of sample and interaction are given.

Supplementary Table 3 for Experiment 3. Ratings and significance testing (ANOVA) results of perceived intensity (antilogged values) of overall taste, sweet, salty, sour, bitter and umami where MPG was used as the umami tastant.

	Perceived intensity (mean of antilogged gLMS intensity ratings)					
Sample	Total intensity	Sweet	Salty	Sour	Bitter	Umami
S	29.2^{cd}	28.6^{a}	2.2^{c}	1.2^{c}	1.3^{c}	1.1^{d}
U+S	35.3^{abc}	28.1^{a}	4.2^{c}	2.0^{c}	3.4^{a}	14.5^{b}
N	23.5^{d}	1.0^{c}	22.5^{a}	1.6^{c}	3.3^{c}	2.4^{cd}
U+N	34.2^{bc}	1.3^{c}	25.2^{a}	1.6^{c}	2.0^{a}	18.9^{b}
C	29.6^{cd}	1.4^{c}	1.5^{c}	26.3^{a}	5.8^{bc}	1.1^{d}
U+C	36.0^{abc}	1.3^{c}	3.7^{c}	28.8^{a}	6.1^{bc}	15.7^{b}
Q	32.8^{bc}	1.1^{c}	1.5^{c}	1.2^{c}	29.7^{a}	1.4^{d}
U+Q	38.5^{ab}	1.1^{c}	2.7^{c}	3.4^{c}	32.4^{a}	15.8^{b}
U	29.0^{cd}	1.3^{c}	3.1^{c}	1.3^{c}	3.8^{bc}	27.2^{a}
U+S+N+C+Q	42.2^{a}	21.6^{b}	16.7^{b}	13.2^{b}	9.7^{b}	7.2^{c}
df of Sample	9	9	9	9	9	9
df of Interaction	99	99	99	99	99	99
F-value of Sample Effect	3.98	65.36	34.69	37.19	26.64	21.49
Sample significance (p)	0.0002	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

^{abcde} Values within a column which don't share a common superscript are significantly different in means ratings of the perceived magnitude from Tukey's HSD test at the 95% confidence interval. S = sucrose; N = sodium chloride; C = citric acid; Q = quinine hemisulfate salt monohydrate; U = potassium L-glutamate monohydrate (MPG). *df* = degrees of freedom of interaction, noting that the main effect of sample (F-value of sample) was determined by dividing the variance of sample by the variance of the interaction (MSsample/MSinteraction) hence both the *df* of sample and interaction are given.