

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

Article

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: 10.1016/j.foodqual.2021.104503 Available at https://centaur.reading.ac.uk/102035/

It is advisable to refer to the publisher's version if you intend to cite from the work. See <u>Guidance on citing</u>.

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

Publisher: Elsevier

All outputs in CentAUR are protected by Intellectual Property Rights law, including copyright law. Copyright and IPR is retained by the creators or other copyright holders. Terms and conditions for use of this material are defined in the <u>End User Agreement</u>.

www.reading.ac.uk/centaur



CentAUR

Central Archive at the University of Reading

Reading's research outputs online

1	Interactions of umami with the four other basic tastes in equi-intense aqueous
2	solutions
3	Authors: Sijia Wang ^a , Maria Dermiki ^b , Lisa Methven ^a , Orla B Kennedy ^a , Qiaofen
4	Cheng ^{a*}
5	^a Department of Food and Nutritional Sciences, University of Reading, Whiteknights,
6	Reading, RG6 6DZ, UK
7	^b Department of Health and Nutritional Sciences, Institute of Technology Sligo, Ash
8	Lane, Sligo, F91 YW50, Ireland
9	*Corresponding author: Dr Qiaofen Cheng, Department of Food and Nutritional
10	Sciences, University of Reading, Whiteknights, Reading, RG6 6DZ, UK. Tel.: +44
11	118 378 8719. Email address: q.cheng@reading.ac.uk
12	
13	Highlight
14	• Umami taste does not enhance or suppress sweet, salty, sour or bitter in equi-
15	intense solutions.
16	• Sweet, salty, sour and bitter significantly suppress umami taste in equi-intense
17	solutions.
18	• Sodium chloride plus glutamate tastants maintained salty and savoury taste
19	perception.
20	
21	Key words
22	Umami, salty, taste, mixtures, suppression, equi-intense
23	

24 Abstract

25 Previous research has shown that the addition of equi-intense concentrations of taste compounds leads to mixture suppression, with sweetness being the least suppressed 26 taste while being the strongest suppressor of the other taste stimuli. However, perceived 27 intensity of umami (savoury) within complex mixtures is less defined. Since 28 maintaining savoury taste of foods at reduced salt levels is a growing need, this study 29 aims to investigate the role of umami in complex taste systems. Initially the 30 concentrations of single tastants were adjusted until a trained sensory panel rated them 31 32 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 33 as binary and quinary systems. The first two sets utilised monosodium glutamate 34 (MSG) as the umami tastant; one set without balancing the sodium level in MSG 35 36 (sodium unbalanced) and another set accounting for it by the addition of sodium at an 37 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 38 to overcome the confounding influence of sodium. All samples were rated by trained 39 40 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 41 (p > 0.05); whereas sweet, salty, sour and bitter significantly suppress the perception of 42 umami in both binary and quinary systems (p < 0.05). 43

44

46 **1. Introduction**

Cross-modal interactions between two or more sensory modalities, have been 47 investigated as a strategy for the reduction of salt and sugar (Ponzo et al., 2021). For 48 example, odour-taste interactions have been explored for the reduction of sugar 49 (Velazquez et al., 2020) and the reduction of salt (Thomas-Danguin, Guichard & Salles, 50 2019; Emorine et al., 2021). Mojet, Heidema and Christ-Hazelho (2004) described how 51 52 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 53 54 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) 55 is used to replace sodium chloride (NaCl) it can increase bitterness in the final product; 56 however, Abu et al. (2018) found that adding sweetness (via trehalose or sucrose) to a 57 KCl/NaCl mixture effectively reduced bitterness without changing saltiness. Therefore 58 59 taste-taste interactions are of relevance to the food scientist, with applications in salt and sugar reduction continuing to be a growing interest. 60

61 Psychophysical functions are used to study and express relationships between a stimulus and a response, or perceived sensation, such as taste. For individual taste 62 63 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 64 is dependent on both the specific tastant and whether the concentration is at relatively 65 low levels (just above threshold, accelerating relationship), moderate levels (linear 66 relationship) or high levels (decelerating relationship) (Bartoshuk, 1975; McBride, 67 1987). 68

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 78 (1975) found that tastants suppressed each other. The extent of suppression was 79 dependent upon the function of the individual tastant; tastes where perception increased 80 sharply with increasing concentration tended to cause greater suppression. Similarly on 81 82 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 83 determined by the perceptual intensity of the individual stronger components, and the 84 sweetness and sourness of the mixture tended to suppress each other. Taking a 85 86 modelling approach to understand the psychophysics of taste interaction, Schifferstein 87 and Frijters (1993) concluded that a summation model (addition of individual component intensities) was sufficiently able to predict total taste intensity of a mixture. 88

89 Since many foods are formulated with tastants at moderate and not extreme levels, it is 90 likely that the influence of taste stimuli in the linear phase of the psychophysical curve 91 might be the most relevant. The approach taken by Green et al. (2010) focused on taste 92 mixtures combined at perceptually equi-intense moderate (not extreme) concentrations. They tested taste interactions in the four taste mixtures (salt, sweet, bitter and sour) 93 using equi-intense concentrations of sodium chloride, sucrose, quinine sulfate and citric 94 acid. Moreover, four tastes qualities in binary, ternary and quaternary mixtures were 95 96 also investigated. They concluded that suppression between stimuli in binary mixtures could predict taste perception in more complex combinations. For example, the sweet 97 taste of sucrose tended to be the least suppressed quality, whereas it was a potent 98 99 suppressor to all other tastes.

100 Umami tastants are widely used as flavour enhancers in food products, and especially101 in developing salt-reduced foods. In practice such enhancement may result from

complex ingredients, such as yeast extracts, that comprise both amino acids (especially 102 glutamate) and 5'- nucleotides. However, literature often focuses on the understanding 103 of simpler systems. A review paper by Maluly et al (2017) recommended that 104 monosodium glutamate (MSG) could be used to reduce NaCl in a broad range of foods. 105 In specific applications, Yamaguchi and Takahashi (1984) demonstrated that MSG 106 107 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 108 109 guanosine-5'-monophosphate (GMP), a much stronger umami taste can be achieved. Yamaguchi and Kimizuka (1979) found that the perceived umami intensity was 110 affected by the ratio of IMP to MSG, and more recently Yamaguchi summarized that 111 maximum taste intensity could be achieved with a 70:30 ratio of IMP to MSG 112 (Yamaguchi, 1998). In using a combination of umami tastants, Dos et al. (2014) found 113 114 that MSG, disodium inosinate, disodium guanylate could enhance flavour and maintain saltiness at 50% reduced NaCl when added into fermented cooked sausages. 115

However, there is limited understanding about how MSG performs in mixture of 116 tastants, and how it interacts with other tastants, especially at equi-intense levels. 117 118 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. 119 The early study by Woskow (1969), investigated the effects of umami on other tastes, 120 but not vice versa. The study used a series of 50:50 combination of disodium 5'-121 122 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 123 124 sweetness and saltiness but suppress sourness and bitterness. Reporting on work from their laboratory in 1979, Yamaguchi (1998) noted that MSG slightly enhanced saltiness 125 126 from NaCl, but only at high MSG concentrations, and found that NaCl had no 127 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 128 129 no influence on sweet, salt, sour and bitter, while at supra-threshold concentrations it 130 suppressed sweet and bitter tastes and enhanced salt perception.

The findings of Kemp and Beauchamp (1994) for bitterness suppression corroborates 131 the work of Woskow (1969), which is perhaps unsurprising as the levels of bitter 132 tastant, quinine sulfate, were relatively similar (0.007 and 0.025 mM respectively) in 133 the two studies and the perceived intensity of MSG at the medium level was similar to 134 the recorded umami intensity of the two ribonucleotides in the earlier study. However, 135 136 for saltiness, Woskow (1969) concluded that ribonucleotides enhanced salty taste at moderate concentration (≥ 0.2 mM), whereas Kemp and Beauchamp (1994) reported 137 138 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 139 to sweet taste, the conflicting result is likely to be due to the difference in sucrose levels 140 used between the two studies. Sweetness was enhanced when the sucrose levels was 141 5% (w/v) or 0.16 M (Woskow, 1969), whereas it was suppressed when the level was 142 three times lower at 0.05 M (Kemp & Beauchamp, 1994). 143

144 Bitterness suppression was later confirmed by Keast and Breslin (2002b), concluding that when using either MSG or adenosine monophosphate sodium salt (NaAMP), the 145 bitter taste of any of five different bitter tastants was suppressed. However, according 146 147 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 148 perceived. Bitter and umami tastes are mediated via G-protein-coupled receptors, T1Rs 149 and T2Rs which are found in type II taste receptor cells (Bachmanov & Beauchamp, 150 2007). Kim et al. (2015) established that the suppression of bitter taste by umami could 151 occur at a cellular level, by investigating umami-bitter taste interactions with a cell-152 based assay using hTAS2R16-expressing cells. They tested the effect of five umami 153 peptides (Glu-Asp, Glu-Glu, Glu-Ser, Asp-Glu-Ser, and Glu-Gly-Ser) on the bitter 154 155 tastant salicin and found that the glutamayl peptides inhibited the salicin-induced intracellular Ca²⁺ response. Specifically, the Glu-Glu peptide suppressed salicin-156 157 induced activation of hTAS2R16 to a greater extent compared with the probenecid, a specific antagonist of hTAS2R16. 158

Previous studies have considered taste-taste interactions within ternary and quaternary 159 mixtures (Bartoshuk, 1975; Breslin & Beauchamp, 1997; Green et al., 2010). Breslin 160 161 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. 162 However, when salt (sodium acetate) was added the bitterness substantially decreased 163 164 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 165 166 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 167 168 taste stimuli and vice versa, aqueous model systems were established to assess the taste 169 perception using equi-intense taste mixture combinations, where the intensity levels are realistic to levels typically present in foods. Progressing understanding from previous 170 171 literature this study specifically hypothesised that at moderate levels of umami sensation, saltiness would not be enhanced but neither would saltiness suppress umami, 172 anticipating therefore by the summation model that the overall taste perception of a 173 174 savoury system would be increased.

175

176 2. Materials and Methods

177 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.

183 2.2 Stimulus

184 The taste stimuli used (indicated in Table 1) were aqueous solutions of sucrose185 (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-186 Aldrich, Gillingham, UK) for sour (C), quinine hemisulfate salt monohydrate (Sigma-187 Aldrich, Gillingham, UK) for bitter (Q), monosodium glutamate MSG and 188 monopotassium L-glutamate monohydrate (MPG) (Ajinomoto, Paris, France) for the 189 taste quality umami (U). Each tastant solution was prepared in mineral water (Harrogate 190 Spa, UK) a day before the panel session and kept in the fridge (4 °C) overnight. All 191 tastant solutions were taken out of the fridge prior to the test to equilibrate to ambient 192 193 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 194 temperature (22 ± 2 °C). 195

196 2.3 Training

Prior to the data collection, all panelists participated in training on the use of the general 197 labelled magnitude scale (gLMS). Compared to labelled magnitude scale (LMS) first 198 199 developed by Green, Shafer, and Gilmore, (1993), the top of gLMS is defined as 200 "strongest imaginable of any sensation", which is more suitable for this experiment 201 where intensity across modalities is compared (Bartoshuk et al., 2004). The descriptors of the magnitude estimates were "barely detectable", "weak", "moderate", "strong", 202 "very strong" and "strongest imaginable of any sensation" (anchored values on gLMS 203 204 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). 205

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.

211 2.4 Tastants preparation

Each of the three experiments described below in detail, contained a total of 10 tastants, 212 including five single tastant solutions and five tastant mixtures (four binary, one 213 214 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 215 unbalanced (UB) was scored by the panel, which were followed by solutions using 216 217 MSG as the source for umami with sodium balanced (B) (Experiment 2). Finally, the 218 panel was required to taste the third set of solutions (Experiment 3) which were 219 prepared using MPG as the source for umami. For the three experiments, scoring for the samples were completed within two days. 220

221 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.

226 2.4.2 Experiment 2: MSG as the source for umami with sodium balanced (B)

227 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 228 229 that a raised sodium level in samples were perceived as salty taste. To achieve this, 230 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 231 232 concentrations with the mean panel scores being between strong and very strong on the 233 gLMS. The concentration of each tastant was kept constant in each binary and quinary 234 tastant mixture as seen in Table 1.

235 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

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		
С	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		

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

*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).

246 2.5 Sensory evaluation

The experiments were conducted within a standard sensory environment using 247 individual sensory booths, artificial daylight and controlled room temperature (22 \pm 248 249 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 250 251 seconds before swallowing and rating six attributes for each sample as follows: overall 252 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 253 254 water at room temperature) to return the mouth back to a neutral state; an automatic 255 reminder appeared during the countdown of ninety seconds between each stimulus after 256 evaluating consecutive taste samples. Within each experiment scoring sessions 257 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 258 259 other, between replicates and between experiments. Data were captured using the 260 sensory software Compusense® (cloud version, Guelph, Ontario).

261 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.

270 **3. Results**

271 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). 272 The aim was to have all single tastants rated "strong to very strong" on the gLMS (1.52 273 to 1.70 on the log scale, or 31.6 to 50.1 exponentiated values) in both the sodium 274 unbalanced and balanced sets. Although panelists were extensively trained on each 275 276 single tastant, saltiness and sourness were rated slightly lower than "strong". However, 277 the mean ratings (exponentiated data) only fell below this descriptor by a maximum of 278 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 279 "moderate to strong" on the gLMS (1.21 to 1.52 on the log scale, or 15.85 to 31.62 as 280 281 exponentiated values), while the concentration of tastants used was slightly lower in 282 comparison to the MSG set samples.

283 3.1 Intensity of umami

The ratings of perceived intensity of umami in the different experiments are presented 284 285 in Figure 1. It is clear from this figure that the perception of umami was significantly 286 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 287 perceived umami intensity compared to MSG alone (U). The umami sensation was 288 289 reduced from just above "strong" to "moderate" or "weak" in virtually all cases. The 290 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". 291 292 The intensity of umami in the quinary taste systems (U+S+N+C+Q) was the lowest for 293 all experiment sets.

294 3.2 Intensity of other tastes

The ratings of perceived intensity of sweetness, saltiness, sourness and bitterness canbe 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 297 in supplementary Table 1 to 3). This is an unusual phenomenon as all other taste 298 299 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, 300 perception of the other four tastes. Kemp and Beauchamp (1994) concluded that MSG 301 302 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 303 304 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 305 different concentration of the other tastants. The present study used 0.19 M sucrose and 306 0.005 M citric acid for equi-intense perception of "strong to very strong". 307

308 3.3 Overall taste intensity

The ratings of perceived intensity of overall taste in the different experiments are 309 310 presented in Figure 3. Results indicated that the total taste intensity of binary mixtures 311 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 312 sodium chloride with umami mixture (U+N) in MPG set, where the binary mixture was 313 314 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 315 a significantly higher rating compared to the binary mixture with citric acid (U+C) in 316 both MSG sessions, and the binary mixture with sodium chloride (U+N) in sodium 317 balanced set and MPG set (p < 0.05). The perception of all five tastes were all 318 significantly and substantially lower in the quinary mixtures than as single tastants (p 319 < 0.05) in the sodium balanced set and MPG set. In the sodium unbalanced set, sour, 320 bitter and umami tastes were similarly significantly lower in the quinary mixtures than 321 322 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 325 due to the inclusion of 0.015mM NaCl in quinine solution in the sodium balanced set. 326 327 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 328 would lead to a lower intensity of bitterness for quinine solution in sodium balanced set 329 330 (Experiment 2), while it is not the case in sodium unbalanced set (Experiment 1) and 331 MPG set (Experiment 3). As the total overall intensity is determined by the dominant 332 taste (bitterness), as a result, a low overall taste intensity in quinine hemisulfate alone solution (O) was expected compared with that in guinine hemisulfate with umami 333 mixture (U+Q) in sodium balanced set. The binary mixture of MPG and NaCl (U+N) 334 had a significantly higher overall taste intensity than the sample of NaCl (N) alone (p 335 < 0.05). This indicates that umami may enhance the total intensity of a salt solution 336 without enhancing the specific taste modality (saltiness) in the MPG mixture. The 337 binary mixtures of U+N in the MSG sample set had a similar trend, but the differences 338 were not significant (p > 0.05). These differences may be associated with the difference 339 340 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 341 having a significantly and substantially lower overall taste intensity than the quinary 342 343 mixtures except quinine hemisulfate (p < 0.05).

344 3.4 Taste interaction

The testing of the balanced sodium sample set allowed for an unbiased investigation of 345 the influence of glutamate and the perception of all other tastes, and of the effect of 346 347 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 348 same, increasing the confidence in the overall finding that umami from glutamate does 349 350 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 351 tastes suppressed umami (p < 0.05), whereby all binary mixtures had significantly lower 352 umami intensity than MPG alone (p < 0.05), and the quinary mixture was significantly 353

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).

358 **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.

364 Keast and Breslin (2002a) have shown that the concentration of taste stimuli, and the position on the concentration-intensity psychophysical curve could predict the 365 interactions of tastes in taste mixtures. In the current study however, no matter whether 366 it was in the "moderate" perceived intensity region or in "strong" perceived intensity 367 region, the umami taste did not enhance or suppress the perceived intensity of any other 368 369 taste in the binary taste systems; where sweet, salty, sour and bitter all significantly 370 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 371 solutions (Woskow, 1969; Kemp & Beauchamp, 1994) and in foods (Dermiki et al., 372 373 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 374 from this study conclude that umami taste did not affect the salty taste when presented 375 376 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 383 384 swallow procedure, are also responsible for the conflict. Running and Hayes (2017) have previously concluded that taste ratings resulting from model solutions that had 385 been spat out are lower than ratings for swallowed samples on a gLMS scale. Taken 386 together these arguments might infer that umami may enhance salty perception where 387 salty taste is lower. Kawasaki et al. (2016) give an insight into the time over which the 388 389 different tastes are perceived, for example saltiness and sourness tend to be perceived as dominant before swallowing, whereas umami was dominant after swallowing. This 390 finding highlights the effect of the test methodology on the perceived intensity of taste. 391 The sip and spit method was used by Kemp and Beauchamp (1994), while Keast and 392 393 Breslin (2002b) did not include swallowing. But solutions were swallowed in the 394 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 395 duration of impact of taste attributes of umami (MSG), salty (sodium chloride), sour 396 397 (lactic acid) and their binary mixtures using temporal dominance of sensations methodology. They found that the presence of MSG increased the duration of NaCl 398 saltiness but suppressed the sourness of lactic acid. On the other hand, the duration of 399 400 umami taste of MSG was suppressed in the presence of NaCl but was not affected by 401 lactic acid. This means that MSG could increase the duration of salty taste from NaCl 402 rather than enhance the peak intensity. This might imply that where previous studies 403 have reported an enhancement of salty taste, it could have been that the taste duration 404 was extended rather than an increase in maximum intensity. However, our study was 405 specifically set up to test maximum intensity following the sample remaining in the 406 mouth for 5s, and so would not have captured an increase in duration that the Kawasaki study concluded. 407

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 410 panelists in this study were trained to recognise and score umami taste, they were UK 411 412 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 413 functional magnetic resonance imaging (fMRI) was employed, it was confirmed that 414 there was only a slight difference between the positions of the activation regions 415 between umami and salty taste, which led to the conclusion that the basic perception 416 417 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 418 reported that the NaCl solutions with MSG increased responses in the frontal operculum 419 but did not affect the hemodynamic salivary by functional near-infrared spectroscopy 420 (fNIRS) data. This means that the umami induced saltiness enhancement effects occur 421 in the central gustatory processing in the brain. Additionally, this might partly explain 422 why umami, in the MPG model, was found to enhance the total taste intensity of the 423 salt solution, without enhancing the specific taste modality (saltiness). 424

425 The type of panelist used in different studies should also be considered. Trained sensory 426 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 427 they are tasting (Ares & Varela, 2017). Compared with untrained consumers, trained 428 panelists are more sensitive to taste discrimination, and they are significantly more 429 aware of the flavour in the mixture and the intensity of suppression (McBride & Finlay, 430 1989; Prescott, Ripandelli & Wakeling, 2001), although their hedonic perception of the 431 432 product may not fully represent the wide and varied perceptions from untrained 433 consumers (Ares & Varela, 2017). So, one might expect a consumer would synthesise 434 congruent taste information in a way that a trained panelist might not, leading more 435 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 436 437 studies which concluded that umami enhanced salty taste perception were all carried out with trained panelists (Woskow, 1969; Kemp & Beauchamp, 1994; Keast & 438

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.

442 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 443 additivity, the sum of the tastes perceived within the mixture (Green et al., 2010). In 444 fact, their study concluded the sum of the unmixed taste intensities to be much higher 445 than the sum of the taste intensities in the mixture, or the overall taste intensity ratings, 446 447 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 448 taste intensities and the sum of the taste intensities in binary system and quinary mixture. 449 However, it was relatively easy to distinguish each taste in the binary system but much 450 451 more difficult to distinguish each taste in the quinary mixture system, which may lead 452 to a great reduction in intensity compared to a single tastant.

453 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 454 means the relationship between the five basic tastes is only valid at certain taste 455 456 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 457 as the source of umami. Even if the results presented same trend (suppression), the 458 impact of concentration range on perception was uncertain. However, it provides a 459 prediction for the relationship of the five basic tastes when MSG is used as the source 460 of umami at other concentration levels in the future. 461

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 467 complexity of food matrices which affects the perception. In a real food there are cross-468 469 modal interactions between two or more sensory modalities such as taste-flavour or flavour-texture interactions. Additionally, ingredients used in food products are often 470 added at much higher concentrations than in the aqueous model systems to achieve the 471 472 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 473 474 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 475 the salty taste, and 0.3% MSG added to the sausage to compensate the saltiness loss 476 caused by 50% salt reduction in low-sodium fish burgers (Quadros et al., 2015). In 477 contrast, only 0.19% or 0.25% MSG was used in this study. Therefore, the conclusions 478 479 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. 480

The present study employed a trained sensory panel to investigate taste interactions, 481 with limited variability in taste sensitivities. Prescott et al. (2001) concluded that 482 483 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. 484 However, the taste sensitivity is determined by many factors, such as genetic 485 differences in taste receptors, including Tas2R38 gene that is predominantly 486 487 responsible for PROP/PTC (phenylthiocarbamide) tasting (Hayes et al, 2008), and single nucleotide polymorphisms (SNPs) for epithelial sodium channel (ENaC) 488 489 (Chamoun *et al*, 2021). For example, SNPs for the T1R receptors influence perception 490 of sweet and umami taste. Therefore, to truly understand the influence of umami taste 491 in taste mixtures for all consumers, a study considering taste sensitivities to basics tastes 492 (each from more than one tastant) alongside genotyping would be needed in a large population cohort in the future. 493

495 **5.** Conclusions

496 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 497 not enhance or suppress any other taste. Therefore, umami is dissimilar to other tastants 498 which tend to suppress one another. However, the addition of sweet, salty, sour and 499 bitter do significantly suppress the umami taste. The findings of this study are 500 501 significant because they fill the gap that existed in the literature considering the effect 502 of umami taste in taste mixture interactions and have an impact on our understanding 503 of the underlying mechanisms of taste interactions that can be applied in food reformulation. Although umami was not found to enhance salty perception, as 504 hypothesised, neither did it suppress it; hence when used together sodium chloride plus 505 glutamate tastants maintained salty perception in addition to savoury taste perception, 506 507 irrespective of the glutamate salt used. Overall, there is little evidence on the effect of 508 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 509 reasons for this are the different sensory tests used (ranking vs gLMS), the different 510 511 methodology (sip and spit vs swallowing), the different concentrations of tastants and the difference in perception of similar concentrations by the different groups studied. 512 513 Further investigation is needed to determine whether these findings in aqueous solutions apply to real food systems where more complex and cross-modal interactions 514 515 take place.

516

517 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.

522 **References**

- 523 Ares, G. & Varela, P. (2017). Trained vs. consumer panels for analytical testing:
- 524 Fueling a long lasting debate in the field. *Food Quality and Preference*, 61, 79-86.
- Abu, N.B., Harries, D., Voet, H. and Niv, M.Y., (2018). The taste of KCl–What a difference a sugar makes. *Food chemistry*, 255, 165-173.
- 527 Bachmanov, A.A & Beauchamp, G.K. (2007). Taste Receptor Genes. Annual Review
- 528 *of Nutrition*, 27, 389–414.
- 529 Bartoshuk, L. M. (1975). Taste mixtures: Is mixture suppression related to 530 compression? *Physiology and Behavior*, 14(5), 643-649.
- 531 Bartoshuk, L.M., Duffy, V.B., Green, B.G., Hoffman, H.J., Ko, C.W., Lucchina, L.A.,
- 532 Marks, L.E., Snyder, D.J. and Weiffenbach, J.M. (2004). Valid across-group
- 533 comparisons with labeled scales: the gLMS versus magnitude matching. *Physiology* &
- *behavior*, 82(1), 109-114.
- 535 Breslin, P. A. S. & Beauchamp, G. K. (1997). Salt enhances flavour by suppressing
- 536 bitterness. *Nature*, 387, 563-563.
- 537 Cecchini, M., Knaapila, A., Hoffmann, E., Boschi, F., Hummel, T. & Iannilli, E. (2019).
- 538 A cross-cultural survey of umami familiarity in European countries. *Food Quality and*
- 539 *Preference*, 74, 172-178.
- 540 Chamoun, E., Liu A.S. Duizer, L.M., Feng, Z., Darlington, G., Duncan, A.M., Haines,
- 541 J., Ma, D.W.L. (2021). Single nucleotide polymorphisms in sweet, fat, umami, salt,
- bitter and sour taste receptor genes are associated with gustatory function and taste
 preferences in young adults. *Nutrition Research*, 85, 40-46.
- 544 Dermiki, M., Mounayar, R., Suwankanit, C., Scott, J., Kennedy, O., Mottram, D.,
- 545 Gosney, M., Blumenthal, H. and Methven, L. (2013). Maximising umami taste in meat
- 546 using natural ingredients: effects on chemistry, sensory perception and hedonic liking
- 547 in young and old consumers. Journal of the Science of Food and Agriculture, 93(13),
- 548 3312-3321.
- 549 Dos Santos, B., Campagnol, P., Morgano, M. & Pollonio, M. (2014). Monosodium 550 glutamate, disodium inosinate, disodium guanylate, lysine and taurine improve the

- sensory quality of fermented cooked sausages with 50% and 75% replacement of NaCl
- with KCl. *Meat Science*, 96(1), 509-513.
- 553 Emorine, M., Septier, C., Martin, C., Cordelle, S., Sémon, E., Thomas-Danguin, T. and
- 554 Salles, C. (2021). Salt and aroma compound distributions influence flavour release and
- temporal perception while eating hot-served flans. *Molecules*, 26(5), 1300-1317.
- 556 Fuke, S. and Ueda, Y. (1996). Interactions between umami and other flavor 557 characteristics. *Trends in Food Science & Technology*, 7(12), 407-411.
- 558 Green, B.G., Shaffer, G.S. and Gilmore, M.M. (1993). Derivation and evaluation of a
- semantic scale of oral sensation magnitude with apparent ratio properties. *Chemical senses*, 18(6), 683-702.
- 561 Green, B. G., Lim, J., Osterhoff, F., Blacher, K., & Nachtigal, D. (2010). Taste mixture
- interactions: Suppression, additivity, and the predominance of sweetness. *Physiology*& *Behavior*,101, 731-737.
- Hayes, J.E., Bartoshuk, L.M., Kidd, J.R., Duffy, V.B. (2008). Supertasting and PROP
- bitterness depends on more than the TAS2R38 gene. *Chemical Senses*, 33 (3), 255-265.
- 566 Inguglia, E.S., Zhang, Z., Tiwari, B.K., Kerry, J.P. and Burgess, C.M., (2017). Salt
- 567 reduction strategies in processed meat products-A review. *Trends in Food Science &*
- 568 *Technology*, 59, 70-78.
- 569 Kawasaki, H., Sekizaki, Y., Hirota, M., Sekine-Hayakawa, Y. & Nonaka, M. (2016).
- 570 Analysis of binary taste-taste interactions of MSG, lactic acid, and NaCl by temporal
- dominance of sensations. *Food Quality and Preference*, 52, 1-10.
- Keast, R. S. J. & Breslin, P. A. S. (2002a). An overview of binary taste-taste
 interactions. *Food Quality and Preference*, 14, 111-124.
- 574 Keast, R. S. J. & Breslin, P. A. S. (2002b). Modifying the bitterness of selected oral
- pharmaceuticals with cation and anion series of salts. *Pharmaceutical Research*, 19,
- 576 1019-1026.
- 577 Kemp, S. E. & Beauchamp, G. K. (1994). Flavor Modification by Sodium Chloride and
- 578 Monosodium Glutamate. *Journal of Food Science*, 59, 682-686.

- 579 Khetra, Y., Kanawjia, S., Puri, R., Kumar, R. & Meena, G. (2019). Using taste-induced
- saltiness enhancement for reducing sodium in Cheddar cheese: Effect on physico-
- chemical and sensorial attributes. *International Dairy Journal*, 91, 165-171.
- 582 Kim, M., Son, H., Kim, Y., Misaka, T. & Rhyu, M. (2015). Umami-bitter interactions:
- 583 The suppression of bitterness by umami peptides via human bitter taste receptor.
- 584 *Biochemical and Biophysical Research Communications*, 456(2), 586-590.
- 585 Kremer, S., Shimojo, R., Holthuysen, N., Köster, E. & Mojet, J. (2013). Consumer
- acceptance of salt-reduced "soy sauce" foods over rapidly repeated exposure. *Food*
- 587 *Quality and Preference*, 27(2), 179-190.
- 588 Maluly, H.D., Arisseto Bragotto, A.P. and Reyes, F.G., (2017). Monosodium
- 589 glutamate as a tool to reduce sodium in foodstuffs: Technological and safety aspects.
- 590 *Food science & nutrition*, 5(6), 1039-1048.
- McBride, R.L., (1987). Taste psychophysics and the Beidler equation. *Chemical Senses*, 12(2), 323-332.
- 593 McBride, R.L. and Finlay, D.C., (1989). Perception of taste mixtures by experienced 594 and novice assessors 1. *Journal of Sensory Studies*, 3(4), 237-248.
- 595 McBride, R.L. and Finlay, D.C., (1990). Perceptual integration of tertiary taste 596 mixtures. *Perception & psychophysics*, 48(4), 326-330.
- 597 McBride, R.L., (1993). Integration psychophysics: The use of functional measurement
- in the study of mixtures. *Chemical senses*, 18(2), 83-92.
- 599 Mojet, J., Heidema, J. and Christ-Hazelhof, E., (2004). Effect of concentration on taste-
- taste interactions in foods for elderly and young subjects. *Chemical senses*, 29(8), 671-
- 601 681.
- 602 Nakamura, Y., Goto, T., Tokumori, K., Yoshiura, T., Kobayashi, K., Nakamura, Y.,
- Honda, H., Ninomiya, Y. & Yoshiura, K. (2011). Localization of brain activation by
- umami taste in humans. *Brain Research*, 1406, 18-29.
- 605 Onuma, T., Maruyama, H. and Sakai, N. (2018). Enhancement of Saltiness Perception
- 606 by Monosodium Glutamate Taste and Soy Sauce Odor: A Near-Infrared Spectroscopy
- 607 Study. *Chemical Senses*, 43(3), 151-167.

- Prescott, J., Ripandelli, N. and Wakeling, I., (2001). Binary taste mixture interactions
 in prop non-tasters, medium-tasters and super-tasters. *Chemical senses*, 26(8), 9931003.
- 611 Ponzo, V., Pellegrini, M., Costelli, P., Vázquez-Araújo, L., Gayoso, L., D'Eusebio, C.,
- Ghigo, E. and Bo, S., (2021). Strategies for reducing salt and sugar intakes in
 individuals at increased cardiometabolic risk. *Nutrients*, 13(1), 279-296.
- 614 Quadros, D. A., Rocha, I. F. O., Ferreira, S. M. R., & Bolini, H. M. A. (2015). Low-
- sodium fish burgers: Sensory profile and drivers of liking. *LWT Food Science and*
- 616 *Technology*, 63, 236–242.
- Running, C. & Hayes, J. (2017). Sip and spit or sip and swallow: Choice of method
- differentially alters taste intensity estimates across stimuli. *Physiology & Behavior*,
 181, 95-99.
- 620 Schifferstein, H.N. and Frijters, J.E., (1993). Perceptual integration in heterogeneous
- taste percepts. Journal of Experimental Psychology: Human Perception and
 Performance, 19(3), 661-675.
- 623 Thomas-Danguin, T., Guichard, E. and Salles, C., (2019). Cross-modal interactions as
- 624 a strategy to enhance salty taste and to maintain liking of low-salt food: A review. *Food*
- 625 & function, 10(9), 5269-5281.
- 626 Velázquez, A.L., Vidal, L., Varela, P. and Ares, G., (2020). Cross-modal interactions
- 627 as a strategy for sugar reduction in products targeted at children: Case study with vanilla
- 628 milk desserts. *Food Research International*, 130, 108920.
- 629 Woskow, M. H. (1969). Selectivity in flavor modification by 5'-ribonucleotides. *Food*
- 630 *Technology*, 23, 32-37.
- Yamaguchi, S. & Kimizuka, A. (1979). Psychometric studies on the taste of
 monosodium glutamate. *Advances in biochemistry and physiology*, 35-54.
- 633 Yamaguchi, S., & Takahashi, C. (1984). Interactions of monosodium glutamate and
- 634 sodium chloride on saltiness and palatability of clear soup. *Journal of Food Science*,
- **635** 49(1), 82–85.
- 636 Yamaguchi, S. (1998). Basic properties of umami and its effect on food flavour. Food
- 637 *Reviews International*, 14(2&3), 139-176.



640 Figure 1. Ratings of perceived intensity (exponentiated values) of umami in the

641 sodium unbalanced and balanced sets and using MPG as source of umami taste set. S

642 = sucrose; N = sodium chloride; C = citric acid; Q = quinine hemisulfate salt

643 monohydrate; U = monosodium glutamate (MSG) or potassium L-glutamate

644 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:

647 MGS with salt balanced, and Greek letters used for Experiment 3: MPG.

648

649

650

651





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 = monosodiumglutamate (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

672 sodium unbalanced and balanced sets and using MPG as source of umami taste set. S

673 = sucrose; N = sodium chloride; C = citric acid; Q = quinine hemisulfate salt

674 monohydrate; U = monosodium glutamate (MSG) or potassium L-glutamate

675 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:

678 MGS with salt balanced, and Greek letters use for Experiment 3: MPG.

679

680

681

682

683

685

684

686



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
Ν	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
С	38.7 ^{cd}	1.4 ^b	3.6 ^c	31.4 ^a	9.3°	1.0 ^d
U+C	41.3 ^{bcd}	2.2 ^b	5.0 ^c	29.8 ^a	8.3°	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	32.2ª
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
<i>df</i> 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°	2.2 ^c	1.6 ^c	14.4 ^c
Ν	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
С	37.9 ^{de}	2.0 ^c	5.0 ^c	31.2ª	6.0 ^c	1.3 ^e
U+C	42.8 ^{bcde}	1.7 ^c	7.4 ^c	29.1ª	6.7 ^c	13.3 ^{cd}
Q	34.6 ^e	1.4 ^c	5.2 ^c	2.5°	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	31.2ª
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
<i>df</i> 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.

736 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
Ν	23.5 ^d	1.0 ^c	22.5ª	1.6 ^c	3.3 ^c	2.4 ^{cd}
U+N	34.2 ^{bc}	1.3 ^c	25.2ª	1.6 ^c	2.0 ^a	18.9 ^b
С	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°	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
<i>df</i> 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 739 different in means ratings of the perceived magnitude from Tukey's HSD test at the 740 95% confidence interval. S = sucrose; N = sodium chloride; C = citric acid; Q = quinine 741 hemisulfate salt monohydrate; U = potassium L-glutamate monohydrate (MPG). df =742 degrees of freedom of interaction, noting that the main effect of sample (F-value of 743 744 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 745 given. 746

747