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1 **The role of sour and bitter perception in liking, familiarity and choice**
2 **for phenol-rich plant-based foods**

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25 **Abstract**

26 Among factors influencing food preferences and choices, individual differences in taste perception
27 play a key role in defining eating behaviour. In particular, sour and bitter responsiveness could be
28 associated with the acceptance and the consumption of phenol-rich plant-based foods recommended
29 for a healthy diet. The aim of this study was to investigate, in a large population sample, the
30 associations among sour and bitter responsiveness and liking, familiarity and choice for plant-based
31 foods characterized by these target tastes. Adults aged 18 to 60 years (n = 1198; 58% women) were
32 tested for their sour and bitter responsiveness both in water solutions and in food models (pear juice-
33 based beverages modified in citric acid content to induce different levels of sourness: 0.5, 2.0, 4.0
34 and 8.0 g/kg; chocolate pudding samples modified in sucrose content to induce different levels of
35 bitterness: 38, 83, 119, 233 g/kg). Familiarity, stated liking and choice for fruit juices and vegetables
36 varying for sour/bitter taste (high in bitter/sour taste: e.g. grapefruit juice and cauliflower; low in
37 bitter/sour taste: e.g. zucchini and pineapple juice) were measured. Results showed a significant
38 positive correlation between bitter and sour taste perception in water solutions and model foods, as

39 well as a positive correlation between the perceived intensity of the two taste stimuli. Subjects
40 characterized by high responsiveness to the two target stimuli were found to give lower liking scores
41 to foods characterized by sour/bitter tastes and tended to choose less sour/bitter foods compared to
42 less responsive subjects.

43 Thus, food choice for phenol rich plant-based products could be associated with a reduced
44 responsiveness to bitter and sour tastes and a consequent higher acceptance of food products
45 characterized by these taste qualities.

46

47 **Keywords:** taste perception, food preferences, food choice, plant-based diet, food familiarity

48

49 **1. Introduction**

50 It is widely reported that following a balanced diet is one of the key factors to prevent several non-
51 communicable diseases, such as cardiovascular diseases and some types of cancer. An adequate
52 intake of fruit and vegetables is reportedly associated with a reduced risk of all-cause mortality (Aune
53 et al., 2017) as well as pivotal to ensure the recommended daily intake of micronutrients, such as
54 vitamins and minerals (Hartley et al., 2013).

55 Plant-based foods are rich in dietary fibre and several non-nutrient substances including sterols,
56 flavonoids and other antioxidant compounds showing positive health outcomes (Buttriss & Stokes,
57 2008), which could help to prevent weight gain and reduce the risk of obesity (Mytton et al., 2014).
58 Among antioxidant compounds, phenols present in plant-based foods show several pro-healthy
59 activities, including antimicrobial, anti-inflammatory, and chemo-preventive properties (Servili et al.,
60 2014, De Toffoli et al., 2019).

61 Despite the positive impact that the vegetable and fruit consumption plays on subjects' health, there
62 is evidence reporting that plant-based diet represents also a more environmentally sustainable choice
63 compared with animal-based diet. Previous research highlighted that, assuming a constant daily
64 calorie intake, the meat-based food system requires more water, land and energy than the plant-based
65 food system (Pimentel & Pimentel, 2003; FAO, 2017). More recently, this assumption has been also
66 corroborated by other research showing that plant-based diets require fewer natural resources and
67 have less impact on the environment compared with diets rich in animal-based products (Ruini et al.,
68 2015; Davis et al., 2016). In particular, the results obtained by Ruini et al. (2015) suggested that the
69 Mediterranean diet may lead to a lower environmental impact compared to diets that are heavily based
70 on daily meat consumption. The actual approaches applied to make the global food system
71 sustainable, such as food waste reduction, are inadequate given the global population growth and the

72 lack of natural non-renewable resources (Béné et al., 2020). “Going back” to plant-based diets seems
73 to be an important alternative for a more sustainable future (Sabate & Soret 2014).

74 Although it is clear that a diet rich in fruit and vegetables has several positive aspects, adults often
75 fail to reach the recommend daily intake (Appleton et al., 2016), since the consumption of these
76 products has to face with consumer sensory perception, which is determinant in defining food
77 preference and choices. Plant-based foods are characterized by specific sensory attributes, such as
78 bitterness and sourness (Dinnella et al., 2016), due to the presence of polyphenols, isoflavones and
79 other natural compounds, that are responsible of low acceptability possibly leading to a reduced
80 consumption. Sourness and bitterness are innately disliked (Steiner, 1979; Ventura & Mennella,
81 2011) and could represent ‘warning sensations’ that negatively impact on consumers responses
82 (Laureati et al., 2018)

83 The individual variation in taste perception has been largely investigated as responsiveness to the
84 bitter compound 6-n-propylthiouracil (PROP), which is considered as a marker for taste
85 responsiveness, as well as for responsiveness to chemesthetic sensations (e.g. capsaicin; Spinelli et
86 al., 2018; Nolden et al., 2020) that may influence food preferences and eating behaviours (Tepper et
87 al., 2014). More recently, a general taste responsiveness score was proposed to identify subject groups
88 differing for responsiveness to basic tastes (Puputti et al., 2018). However, to date, little attention has
89 been paid to interindividual variations in sour perception and its possible role in defining food
90 preference and choices. Food choice represents an important measure to investigate and describe
91 actual food behaviours beyond food liking (Spinelli et al., 2020). Indeed, there is more to food choice
92 than sensory acceptance per se, as confirmed for example by market failure of new food formulations
93 that previously overcome consumers’ hedonic test (Gutjar et al., 2015).

94 The majority of the studies used standard solutions with varied stimuli concentrations to measure the
95 intensity of perception of a basic taste (see for a review: Cox et al., 2016), while few studies used
96 actual food (Dinehart et al., 2006, Lanier at al., 2005), and foods as models added with varied
97 concentrations of a tastant (Tornwall et al., 2014). However, the sensory experience of eating is
98 complex, and each component may influence food perception, choice and consequent intake
99 (Boesveldt et a., 2018). In fact, food sensory experience is the result of multisensory interactions with
100 all senses, which play together in defining what is liked or disliked (Delwiche, 2004; Small &
101 Prescott, 2005; Hoppu et al., 2020). Thus, responsiveness to tastes in water do not necessarily
102 associates to their perception in food and to related hedonic responses. The extent to which taste
103 responsiveness is associated with food preferences and food consumption has yet to be fully
104 understood and few studies investigated this relationship in representative population samples (Cox
105 et al., 2016).

106 The aims of the present study were to: 1) investigate sour and bitter perception in water solutions and
107 food models in a large population sample; 2) evaluate how taste responsiveness to these two target
108 tastes could be associated with food choices, familiarity with and liking for selected phenol rich plant-
109 based foods.

110

111 **2. Material and method**

112 **2.1 Participants**

113 One thousand one hundred and ninety-eight subjects (women = 58%; age range: 18–60 years; mean
114 men age: 35.9 ± 12.8 and women age: 35.2 ± 13.0) from different cities from Northern, Central and
115 Southern Italy were recruited in the study. Eight research units took part in data collection.
116 Participants were recruited by means of participant universities and research centers' websites,
117 announcements on social networks, article in national newspapers, mailing lists, pamphlet
118 distribution, and word of mouth. Exclusion criteria were pregnancy, breastfeeding, not being born in
119 Italy or having lived less than 20 years in Italy.

120 The study was conducted in agreement with the Italian ethical requirements on research activities and
121 personal data protection (D.L. 30.6.03 n. 196) and in adherence with the principles laid down the
122 Declaration of Helsinki. The protocol was approved by the Ethics Committee of Trieste University
123 and participants gave their written informed consent at the beginning of the study.

124

125 **2.2. Sensory stimuli**

126 *Tastant solutions*

127 Citric acid and caffeine (Sigma-Aldrich) were used to elicit sourness and bitterness perception. Two
128 solutions were prepared by dissolving 4 g/kg of citric acid and 3 g/kg of caffeine in water. These
129 concentrations were chosen based on previously published data (Monteleone et al., 2017).

130

131 *Food models*

132 Pear juice (J) and dark chocolate pudding (P) were selected as appropriate food matrices for testing
133 sour and bitter perception in food models (Monteleone et al., 2017). Ingredients and products
134 distributed by large food companies were used in order to obtain a constant composition and to avoid
135 problems associated with products seasonality. Pudding base formulation was prepared by mixing a
136 commercial pudding powder (ingredients: starch, low-fat cocoa, dextrose, salt, aromas; Cameo
137 S.p.A., Dr. Oetker, Bielefeld, Germany) with 40 g of cocoa powder and 1L of water at 40°C. This
138 mixture was heated in microwave at 900W for 6 min and then at 450W for 4 min. The heating was
139 stopped every 2 min to mix the pudding. A commercial pear juice (ingredients: water, Williams pear

140 puree 50%, sugar, flavourings, acidifier: acid citric; antioxidant: ascorbic acid; Santal, Parmalat
141 S.p.A., Milan, Italy) was used for the base juice formulation. Four pear juice and four dark chocolate
142 pudding samples were prepared by adding, respectively, increased concentrations of citric acid (pear
143 juice: J₁=0.5 g/kg; J₂=2.0 g/kg; J₃=4.0 g/kg and J₄=8.0 g/kg) and sucrose (chocolate pudding: P₁=38
144 g/kg; P₂=83 g/kg; P₃=119 g/kg and P₄=233 g/kg) to base formulations. Tastants concentrations were
145 selected to elicit a variation in the strength of target sensations from weak to strong. Both food models
146 were preliminarily described by a focus group of trained subjects. Pear juice was characterized by
147 sweetness, sourness and pear flavour; chocolate pudding by sweetness, bitterness, chocolate flavour
148 and to a lesser extent by astringency.

149

150 **2.3. Questionnaires**

151 *Food familiarity and stated liking*

152 Familiarity with and stated liking for phenol-rich vegetables were measured using a selection of the
153 IT-Food Familiarity Questionnaire (IT-FFQ) and of the IT-Food Preference Questionnaire (IT-FPQ),
154 developed within the Italian Taste (IT) project (Monteleone et al., 2017). The selection included ten
155 vegetables (carrots salad, zucchini, lettuce and valerian salad, chard, broccoli, asparagus, radish,
156 artichoke, chicory, radicchio and rocket salad) and two fruit juices (grapefruit and pineapple) with
157 varied level of expected bitterness and sourness according to results from a preliminary study
158 conducted at the University of Florence. A Check-All-That-Apply (CATA) questionnaire was used
159 to describe sensory properties of IT-FFQ and IT-FPQ items (De Toffoli et al., 2019). Here only results
160 of “bitterness” and “sourness” attributes in vegetables (201 respondents, 77.7% women; age range
161 18–70; mean age 40.3 ± SD 14.1) and fruit juices (188 respondents, 75.4% women; age range 19–68;
162 mean age 40.1 ± SD 14.3) were reported. To check for the correct use of terms to describe sensory
163 properties, a semantic categorisation task was applied; participants to the CATA test were asked prior
164 to the test to provide the best example coming to their mind of a “sour” and of a “bitter” food,
165 respectively (e.g. “Sour as...”).

166 Familiarity for the selected items was measured using a 5-point labelled scale (1 = I do not recognize
167 it; 2 = I recognize it, but I have never tasted it; 3 = I have tasted it, but I don’t eat it; 4=I occasionally
168 eat it; 5 = I regularly eat it; Tuorila et al., 2001) while stated liking was assessed using the 9-point
169 hedonic scale (1: extremely disliked; 9: extremely liked, Peryam & Pilgrim, 1957). If the participant
170 had never tasted the food in question, he/she could choose the answer “I have never tasted it”. The
171 presentation order of the items was randomized across participants.

172

173 *Food choice*

174 Three vegetables pairs (1: lettuce and valerian salad vs radicchio and rocket salad; 2: zucchini vs
175 asparagus; 3: chard vs chicory) and two fruit juice pairs (1: multivitamin juice - made with carrots,
176 oranges and lemons - vs orange juice; 2: pineapple juice vs grapefruit juice) were selected from the
177 IT-Food Choice Questionnaire (Monteleone et al., 2017) so that the options in each pair significantly
178 differed for bitterness and sourness. For each pair, respondents were asked to indicate which option
179 they would choose in a main meal either lunch or dinner (for vegetables) or breakfast (for fruit juices).
180 The presentation order of the pairs of food items within each meal occasion (breakfast, lunch and
181 dinner) was randomized across participants.

182

183 **2.4. Sensory evaluations**

184 **2.4.1 Training session to the evaluation of taste stimuli and to the use of the scales**

185 Subjects participated in a training session immediately before the evaluation session. In the first part
186 of the training session, subjects were familiarized with the target sensations. For each sensation,
187 appropriate food and beverages examples were recalled and discussed (chicory, black coffee and
188 tonic water were used to recall bitter taste; fresh lemon juice was used as an example of sourness).
189 Participants were encouraged to join the discussion giving their own examples of food and beverages
190 characterized by the target sensations and the appropriateness of their examples provided was
191 collectively discussed. This part of the training session ended with a verbal agreement on the meaning
192 of the target sensations. In the second part of the training session, participants were instructed to the
193 use of the general Labelled Magnitude Scale (gLMS; 0: no sensation; 100: the strongest imaginable
194 sensation of any kind; Bartoshuk et al., 2004) following published standard procedures (Green et al.,
195 1993; Bartoshuk, 2000).

196 Subjects were extensively instructed to treat the “strongest imaginable sensation” as the most intense
197 sensation they could ever imagine experiencing. To familiarize the participants with the scale
198 anchors, they were asked to recall a variety of remembered sensations from different modalities
199 (Bajec & Pickering, 2008; Kalva et al., 2014; Webb et al., 2015). Examples of oral (e.g. the cold of a
200 cube of ice in the mouth; the pungency from hot chili pepper) and non-oral sensations (e.g. the noise
201 of a plane that is flying low, the pain felt when shutting a finger in a door) were proposed to encourage
202 the discussion. To practice on the use of the gLMS, subjects were asked to rate the intensity of the
203 brightest light they had ever seen on a paper ballot. The criterion to conclude that the subjects
204 correctly used the scale was that their ratings were higher than “very strong” and lower than “the
205 strongest imaginable sensation of any kind”. Ratings out of this range were individually discussed
206 and the correct use of the scale clarified (Dinnella et al., 2018). Despite an extensive training was
207 performed with the subjects involved, a measure from an independent modality (e.g., sound, or sight)

208 to corroborate the correct use of the scale was performed but not recorded in the present study.
209 However, a similar approach using recalled sensations has been used in many studies (Parkinson et
210 al., 2016; Duffy et al., 2019; Yang et al., 2019).

211

212 **2.4.2. Evaluation session**

213 Subjects were instructed to hold the whole tastant solution in their mouth for 3 s, then expectorate,
214 wait few seconds and evaluate the perceived intensity. Tastant solutions (10 mL) were presented in
215 80 cc plastic cups identified by a 3-digit code in random order. Food samples (15 g) were presented
216 in 80 cc plastic cups identified by a 3-digit code. Pear juice and dark chocolate pudding samples were
217 presented in independent sets each consisting of four samples presented in random order. Pear juice
218 was presented as first set followed, after a 10 min break, by chocolate pudding.

219 Subjects were instructed to hold the whole pear juice sample in their mouth or to take a full spoon of
220 chocolate pudding, then swallow and evaluate relevant sensory qualities according to the food model
221 considered. For pear juice, participants were asked to evaluate the intensity of sourness, sweetness,
222 and the overall flavour of pear juice. Conversely, the intensity of sweetness, astringency, and the
223 overall flavour of chocolate pudding were chosen to evaluate the perception of the chocolate pudding.
224 Only sourness in pear juices and bitterness in chocolate puddings were here considered for data
225 analysis. The intensity of each sensation was rated on a gLMS and after each sample, subjects rinsed
226 their mouth with water for 30 s, ate some plain crackers for 30 s, and finally rinsed their mouth with
227 water for a further 30 s. Evaluations were performed in individual booths under white lights. After
228 the tasting session, participants filled in the questionnaires. Data were collected with the software
229 Fizz (ver. 2.51. A86, Biosystèmes).

230

231 **2.5. Data analysis**

232 Cochran's Q test was applied to data from CATA questionnaire to check for significant differences
233 in sour/bitter citation among vegetables and fruit juices. Depending on the level of expected
234 bitterness/sourness expressed by participants, vegetables and fruit juices were assigned to either the
235 "*High bitter/sour*" or to the "*Low bitter/sour*" group. McNemar's *post hoc* test was performed as
236 multiple comparison test.

237 Subjects were divided into three age groups: group 1=18–30 years (45%), group 2=31–45 years
238 (28%) and group 3=46–60 years (27%). The age distribution of men and women was not significantly
239 different according to chi-square test ($\alpha = 0.05$). The normality assumption of continuous data was
240 tested by Skewness and Kurtosis.

241 Responsiveness to sour and bitter tastes in water solutions was investigated by means of Two-way
242 ANOVA models considering gender (women and men), age (group 1, group 2 and group 3) as well
243 as their interaction as factors. Participants' responsiveness to the target tastes in pear juice and
244 chocolate pudding samples was assessed by separate ANOVAs considering gender, age, samples
245 (four levels) and their second/third order interactions as factors. When a significant difference
246 ($p<0.05$) was found, the LSD *post hoc* test was performed as multiple comparison test.

247 Correlations between taste responsiveness in water solutions and food models were examined using
248 Pearson's correlation coefficient with a minimum significance level defined as $p<0.05$.

249 Subjects were segmented according to their responsiveness to both sour and bitter tastes in water
250 solutions by means of Hierarchical Cluster Analysis.

251 Two familiarity scores were computed for each subject as the sum of ratings given to high bitter/sour
252 items (*FAM_High bitter/sour*) and to low bitter/sour items (*FAM_Low bitter/sour*) of the food
253 familiarity questionnaire (range from 1 to 5). Two liking scores were computed for each subject as
254 mean of the liking ratings for to high bitter/sour items (*LIK_High bitter/sour*) and to low bitter/sour
255 items (*LIK_Low bitter/sour*) of the food preference questionnaire (range from 1 to 9). Options within
256 the pairs of the Food Choice Questionnaire were coded as "0" if the low bitter/sour option was chosen
257 and "1" if the high bitter/sour option was selected. For each subject, a choice index (*CHO_Index*)
258 was then calculated as the sum of the choices of the bitter/sour option (range from 0 to 5). Differences
259 in familiarity, liking and choice scores between the clusters with different taste responsiveness were
260 evaluated by means of separate ANOVAs and then displayed using rain cloud plots. R 4.0.2 (R Core
261 Team, 2020) was used for this latter graphical representation. Partial eta squared (η^2 values: 0.01
262 small; 0.06 medium; 0.13 large; Cohen, 1988) was applied to evaluate the effect size. All the analyses
263 were performed using IBM SPSS Statistics for Windows, Version 24.0 (IBM Corp., Armonk, NY,
264 USA), with the exception of the CATA data that were analysed using XLSTAT 19.4.1 (Addinsoft).

265

266 **3. Results**

267 **3.1. Differences for expected bitterness and sourness among questionnaire items**

268 Results of the semantic categorisation task showed that the number of subjects who provided as
269 example a term that was ambiguous or not correct was negligible (3.3% in the case of bitterness, 1.6%
270 in the case of sourness), thus indicating that the subjects understood the concept of sour and bitter
271 taste. Cochran's Q test results obtained in the preliminary study applying CATA methodology are
272 reported in **Table 1**.

273

274

275 **Table 1.** Percentage of participants who selected the terms “bitter” and “sour” in the CATA
 276 experiment for selected vegetables and fruit juices and their consequent classification in *Low* and
 277 *High bitter/sour*. Different letters by columns within each food products category (vegetables and
 278 fruit juices), indicate significant differences ($p<0.05$) according to McNemar’s test.
 279
 280

| Food item | Bitter | Sour |
|--------------------------------|-------------------|-------------------|
| <i>Vegetables</i> | | |
| <i>Low bitter/sour</i> | | |
| Carrots salad | 3 ^a | 6 ^{ab} |
| Zucchini | 12 ^b | 4 ^a |
| Lettuce and valerian salad | 19 ^{bc} | 6 ^{ab} |
| Broccoli | 24 ^{cd} | 6 ^{ab} |
| Chard | 27 ^{cd} | 6 ^{ab} |
| <i>High bitter/sour</i> | | |
| Asparagus | 35 ^{de} | 13 ^{bc} |
| Radish | 46 ^e | 22 ^c |
| Artichoke | 63 ^f | 15 ^{bc} |
| Chicory | 82 ^g | 19 ^c |
| Radicchio and rocket salad | 82 ^g | 20 ^c |
| <i>p-value</i> | <0.0001 | <0.0001 |
| <i>Fruit juices</i> | | |
| <i>Low bitter/sour</i> | | |
| Multivitamin juice | 12 ^a | 55 ^a |
| Pineapple | 11 ^a | 45 ^a |
| <i>High bitter/sour</i> | | |
| Orange juice | 29 ^b | 70 ^b |
| Grapefruit | 75 ^c | 75 ^b |
| <i>p-value</i> | <0.0001 | <0.0001 |

281

282 3.2. Taste perception in water solutions and food models

283 No significant gender effects on sour and bitter perception in water solutions were found. Only weak
 284 tendencies have been highlighted for sour and bitter perception according to age ($F_{(2,1192)}=2.72$,
 285 $p=0.06$, $\eta^2= 0.005$; $F_{(2,1192)}=2.21$, $p=0.11$, $\eta^2= 0.004$, respectively), with the youngest group of

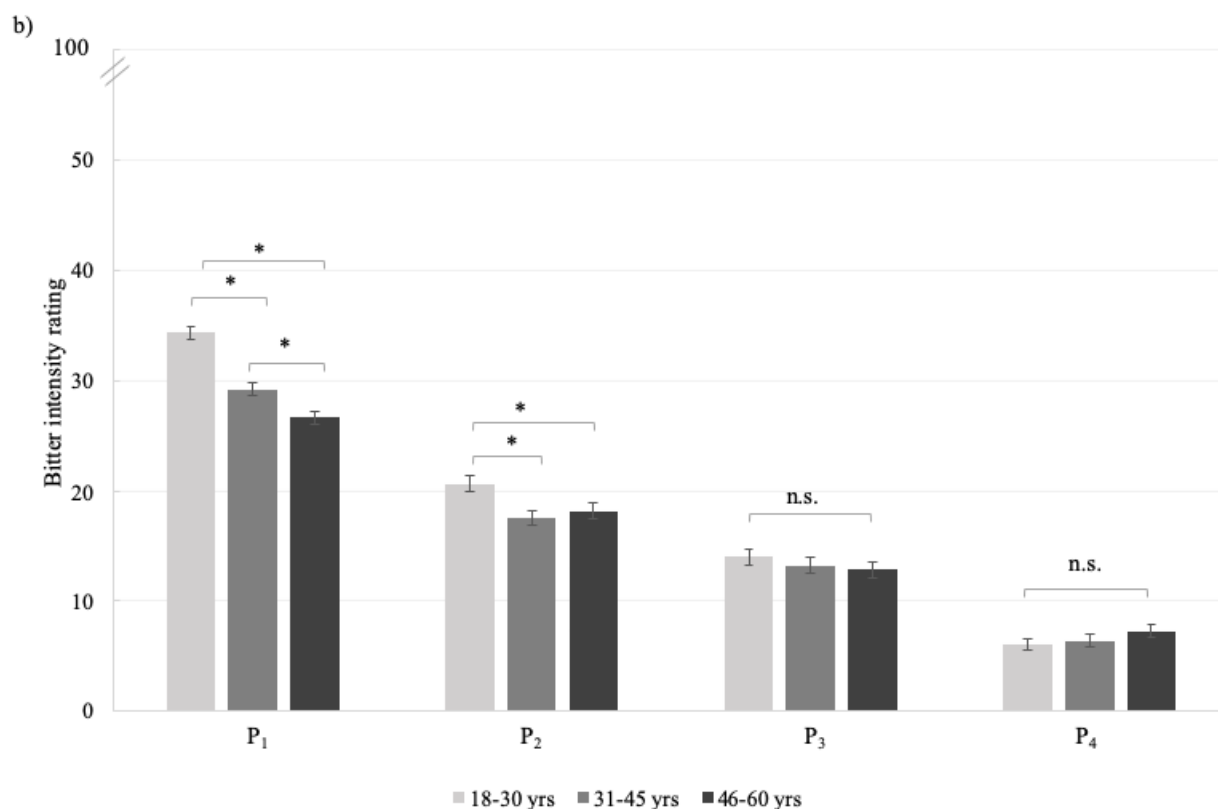
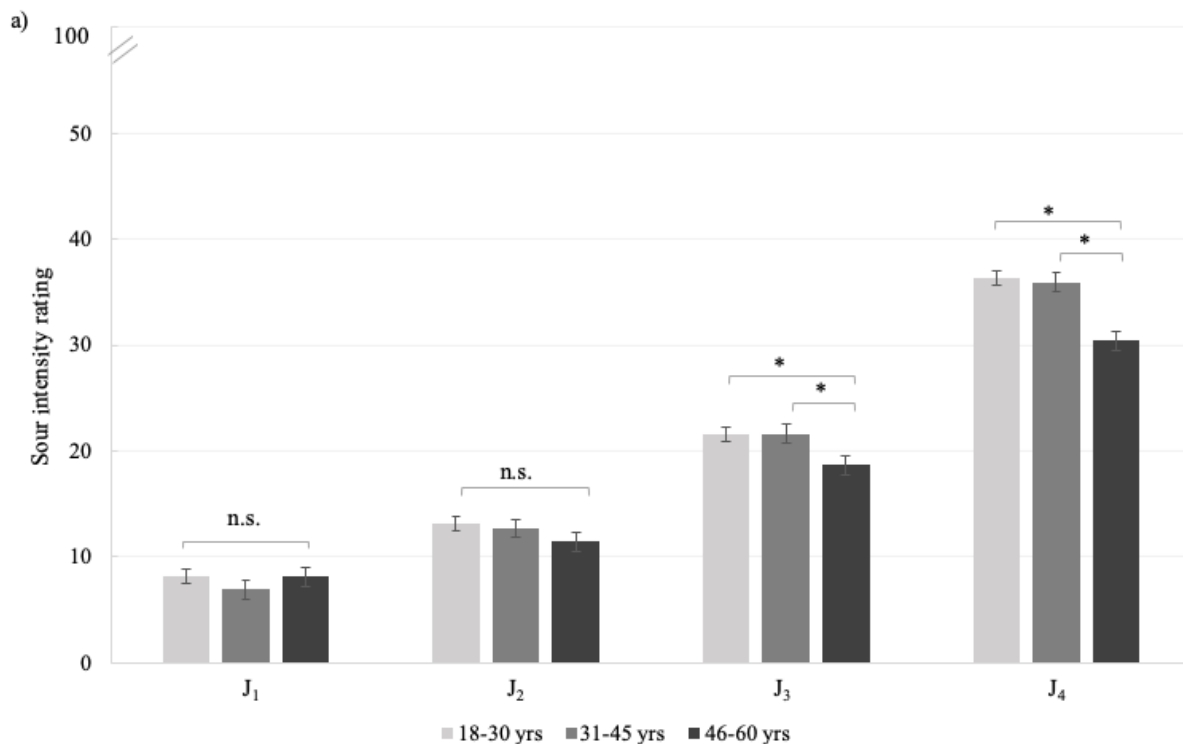
286 subjects (18-30 years old) that tended to be more responsive compared with subjects aged 31-45 and
287 46-60 years.

288 Considering the pear juice and chocolate samples, results revealed a significant effect of the main
289 factor sample ($F_{(3,4768)}=674.90$; $p<0.000$; $\eta^2= 0.29$; $F_{(3,4768)}=647.73$; $p<0.0001$; $\eta^2= 0.29$;
290 respectively). Sour intensity ratings systematically increased from J₁ (7.7 ± 0.4) to J₄ (34.2 ± 0.4) in
291 pear juice samples and bitterness systematically decreased from P₁ (30.0 ± 0.4) to P₄ (6.6 ± 0.4) in
292 chocolate pudding samples. The main factor gender was not significant for sourness and bitterness in
293 model foods.

294 Age was associated with the perceived intensity of both sourness in pear juice and bitterness in
295 chocolate but to a lesser extent ($F_{(2,4768)}=12.67$; $p<0.0001$; $\eta^2= 0.005$; $F_{(2,4768)}=19.19$; $p<0.0001$; $\eta^2=$
296 0.008 , respectively).

297 In both model foods the interaction age*samples (**Figure 1a-b**) showed a significant but very
298 small/small effect on sour and bitter responsiveness ($F_{(6,4768)}=3.66$, $p<0.001$; $\eta^2= 0.005$; $F_{(6,4768)}=9.20$,
299 $p<0.0001$, $\eta^2= 0.01$ respectively.). An age effect was found on intensity ratings only in samples where
300 the intensity of target sensations was rated at moderate level or higher. Samples J₃ and J₄ were rated
301 lower in sourness by subjects aged 46 to 60 years than younger (18-30 and 31-45 years), which did
302 not significantly differ from each other. Bitterness intensity decreased with increasing age in sample
303 P₁ and it was rated higher by subjects aged 18-31 years than older (31-45 and 46-60 years), which
304 did not significantly differ from each other. The lack of significant differences due to age in sample
305 J₁ and J₂ and P₃ and P₄ is possibly due to a floor effect induced by the low intensity level of the target
306 sensations in these samples (ranging from weak to less than moderate).

307



308

309

310 **Figure 1a-b.** Sour (a) and bitter (b) mean intensity ratings (\pm SEM) by samples (pear juice samples:
 311 J₁ - J₄; chocolate pudding samples: P₁ - P₄) and age groups (18-30; 31-45; 46-60 years old). * $p < 0.05$;
 312 n.s. not significant
 313

314 The interaction age*gender showed a significant but very small effect ($F_{(2,4768)}=4.06$, $p < 0.05$; $\eta^2=$
 315 0.002) only on sour intensity ratings. In particular, among subjects of 31-45 years, men gave

316 significant lower intensity ratings (18.4 ± 0.6) compared to women (20.2 ± 0.5), while no gender
 317 differences were found in the other age groups (group 1 and group 3). The interaction gender*sample
 318 was significant ($F_{(3,4768)}=3.02$, $p<0.05$; $\eta^2= 0.002$) only on bitter intensity ratings. Gender-related
 319 differences have been found only for sample P₁ which was perceived as more bitter by women (31.0
 320 ± 0.5) compared to men (29.1 ± 0.6). The other interactions were not significant.

321 Pearson correlations coefficients (**Table 2**) highlighted a significant positive correlation among sour
 322 intensity perceived in water solution and in pear juice samples. The correlation became stronger with
 323 the increasing amount of citric acid in the pear juice. A significant positive correlation was also found
 324 between bitter intensity perceived in water solution and in chocolate pudding samples. The correlation
 325 became weaker with the increasing amount of sucrose as the intensity of the bitterness decreased.
 326 Moreover, bitter and sour perception were always weakly but positively correlated to each other both
 327 in water solution and food models. For example, the sourness perception in samples J₄ with the higher
 328 amount of citric acid was significantly and positively correlated with the bitterness perception in the
 329 chocolate pudding sample with the lower amount of sugar P₁ (most bitter). Pearson correlations
 330 performed with consumers split according to the three-age groups revealed similar results (see
 331 supplementary material).

332

333 **Table 2.** Pearson correlation coefficients among taste perception (S= sour, B=bitter) in water solution
 334 and model foods (pear juice with increasing citric acid: J₁=0.5 g/kg; J₂=2.0 g/kg; J₃=4.0 g/kg and
 335 J₄=8.0 g/kg; Chocolate pudding with increasing sugar: P₁=38 g/kg; P₂=83 g/kg; P₃=119 g/kg and
 336 P₄=233 g/kg)

337

| | S_ water | S_ J ₁ | S_ J ₂ | S_ J ₃ | S_ J ₄ | B_ water | B_ P ₁ | B_ P ₂ | B_ P ₃ | B_ P ₄ |
|-------------------|----------|-------------------|-------------------|-------------------|-------------------|----------|-------------------|-------------------|-------------------|-------------------|
| S_ water | 1 | | | | | | | | | |
| S_ J ₁ | .17 | 1 | | | | | | | | |
| S_ J ₂ | .24 | .51 | 1 | | | | | | | |
| S_ J ₃ | .30 | .38 | .54 | 1 | | | | | | |
| S_ J ₄ | .35 | .26 | .47 | .63 | 1 | | | | | |
| B_ water | .36 | .12 | .19 | .19 | .27 | 1 | | | | |
| B_ P ₁ | .31 | .19 | .24 | .30 | .42 | .37 | 1 | | | |
| B_ P ₂ | .24 | .22 | .26 | .26 | .33 | .29 | .58 | 1 | | |
| B_ P ₃ | .22 | .26 | .28 | .31 | .29 | .25 | .45 | .53 | 1 | |
| B_ P ₄ | .14 | .28 | .26 | .15 | .17 | .15 | .19 | .35 | .41 | 1 |

338 All values are significant at $p < 0.01$

339

340 **3.3 Consumers segmentation according to sour and bitter taste responsiveness**

341 Sour and bitter intensity in water were used as a general index to classify subjects according to their
 342 responsiveness to target tastes. Two clusters were identified showing significant differences in sour
 343 ($F_{(1,1196)}=1456.46$; $p<0.000$; $\eta^2=0.55$) and bitterness perception ($F_{(1,1196)}=418.71$; $p<0.000$; $\eta^2=0.26$).

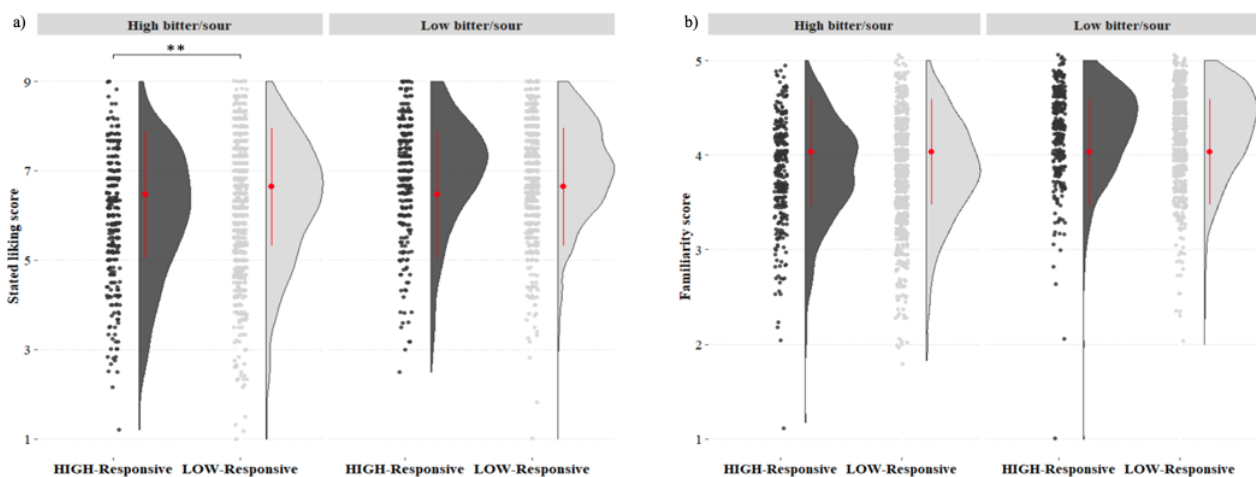
344 In particular, Cluster 1 (*HIGH_Responsive*; n=309) showed higher responsiveness to both the target
 345 tastes (sour: 60.2 ± 0.8 ; bitter: 49.5 ± 1.0) compared to Cluster 2 (*LOW_Responsive*, n= 889; sour:
 346 25.0 ± 0.5 ; bitter: 25.5 ± 0.6). According to χ^2 test, age and gender distributions were not significantly
 347 different between clusters ($p>0.05$).

348

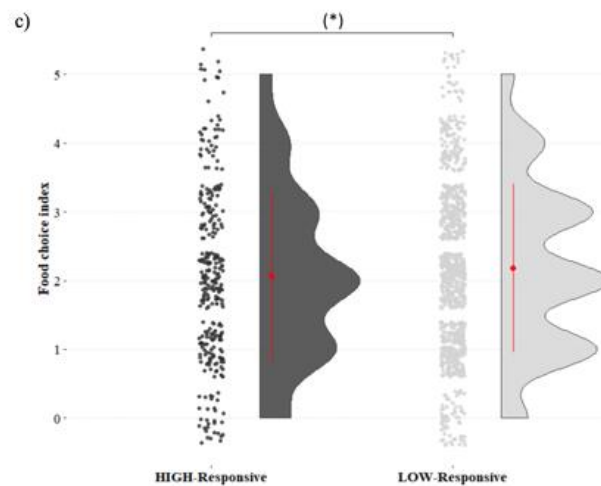
349 **3.4. Associations among sour/bitter responsiveness and familiarity with, liking for and choice of** 350 **plant-based foods**

351 Clusters significantly differed in liking scores for *High bitter/sour* vegetables and fruit juices (F
 352 $(1:1193)=10.19$; $p<0.001$; $\eta^2=0.06$) (**Figure 2a**). Consumers more responsive to these target tastes
 353 (*HIGH_Responsive*) gave significant lower liking scores to *High bitter/sour* vegetables and fruit
 354 juices (6.0 ± 0.08) compared to less responsive subjects (*LOW_Responsive*, 6.3 ± 0.05). No
 355 significant differences between clusters were observed for liking scores for *Low bitter/sour* group (F
 356 $(1:1193)= 0.52$; $p=0.47$). Familiarity scores for both *High* and *Low bitter/sour* items were not
 357 significantly different by cluster (*High bitter/sour*: F $(1:1188)=0.02$; $p=0.89$; *Low bitter/sour*:
 358 F $(1:1188)=0.67$; $p=0.80$) (**Figure 2b**). Clusters tended to differ in food choice score ($p<0.10$) with
 359 *HIGH_Responsive* subjects showing a lower choice for *High bitter/sour* food (2.0 ± 0.07) compared
 360 to *LOW_Responsive* subjects (2.2 ± 0.04) (**Figure 2c**). Results split according to the three-age groups
 361 revealed that the differences in eating behavioural variables by clusters were mainly associated with
 362 subjects aged 18-30 years (see supplementary material).

363



364



365

366 **Figures 2a-c.** Raincloud plot showing the differences on food stated liking scores (a), familiarity
 367 scores (b) and food choice index (c) for *High* and *Low sour/bitter* foods as a function of *HIGH-*
 368 *Responsive* and *LOW-Responsive* clusters. The plots provide a representation of data distribution (the
 369 ‘cloud’), individual raw observations (the ‘rain’), the mean (red filled circle) \pm SD (perpendicular). *
 370 $p < 0.05$; (*) $p < 0.10$.

371

372

373 4. Discussion

374 Sour and bitter perception in water solutions and food matrices were evaluated in a large population
 375 sample to investigate if responsiveness to these target tastes was associated with food choices,
 376 familiarity with and liking for specific phenol rich plant-based foods (vegetables and fruit juices).

377 The present results highlighted a weak but significant positive correlation between the perception of
 378 sour and bitter tastes in water solutions. In this vein, Cattaneo and colleagues (2019), have recently
 379 reported a positive correlation between sour and bitter thresholds in a small group of healthy adults.

380 Moreover, clusters based on tastant solution perception (more sensitive, semi-sensitive, and less
 381 sensitive tasters) have been identified by Puputti et al., 2018 involving a large population sample.

382 The authors highlighted that the membership in a taste cluster could be partially forecasted by the
 383 sensitivity to other taste modalities. This correlation among tastes mediated by different mechanisms,

384 G-coupled protein receptors for bitter and ion channels for sour (Drayna, 2005), could be explained
 385 by a dichotomy in taste coding for pleasant compounds, such as sweet and savoury, versus those
 386 perceived as dangerous, such as sour and bitter stimuli (Hladik et al., 2002). It could be questioned

387 that the correlations here highlighted could be due to the well-established sour-bitter confusion
 388 (Robinson, 1970; Gregson & Baker, 1973). However, prior to tasting, extensive instructions were

389 provided by the experimenters to the subjects to avoid this misperception. Moreover, in this study
 390 sourness and bitterness were evaluated in different food samples (the former on pear juices and the

391 latter on chocolate puddings). It is also worth considering that sourness was evaluated for a pure

392 stimulus in water and for a fruit juice added with citric acid. The intensity of sourness in fruit juice
393 significantly increases with citric acid concentration (see fig. 1a) thus it is reasonable to assume that
394 ratings refer to sour taste and not to bitter taste. Bitterness was rated in a water solution of a pure
395 stimulus and in chocolate added with increasing amount of sugar. Bitterness regularly decreases as
396 effect of suppression by sweetness (see fig. 1b). All these considerations make unlikely the confusion
397 between the two sensations.

398 The present results depicted also a positive correlation between sour/bitter perception in water
399 solutions and in food matrices with correlations becoming stronger in samples characterized by higher
400 intensity of the two target tastes. High responsive subjects to bitter taste seems also to be high
401 responsive to sour, both in water and in food models. Several studies have investigated how taste
402 sensitivity varies among individuals and how this is related to food consumption and subsequent
403 consumer health status (see for a review: Cox et al., 2016). Several authors focussed their attention to
404 sweet and salty perception that could be directly associated with the consumption of food rich in
405 calories and fats. Similarly, bitter perception and food liking represents a widely investigated field of
406 research, while less attention has been paid to sour taste. Moreover, research has been conducted
407 using solution-based approaches to measure hedonic responses (e.g. Drewnowski et al., 1985; Salbe
408 et al., 2004); this can help in modelling perceptual mechanisms but fails to represent the daily
409 experience with foods. Taste responsiveness measured using real foods could provide instead deeper
410 information on food preferences and choice even if fewer studies using this approach are available
411 (e.g. Dinehart et al., 2006; Tornwall et al., 2014; Proserpio et al 2016; Dinnella et al., 2018).

412 Looking to age effects on bitter and sour responsiveness older subjects (46-60 years old) tended to
413 give lower intensity rating scores in water solutions compared to younger subjects. This tendency
414 was found to become significant, although the effect size was always small, considering bitter and
415 sour perception in food models. These results are supported by previous evidence reporting a decline
416 in the gustatory function, mainly investigated using aqueous solutions, in the older population that
417 could be due to several factors, including physiological changes such as a taste receptor cells
418 dysfunction (Methven et al., 2012). Even if evidence about the extent and type of taste loss with
419 aging, sour and bitter tastes seem to be the most affected taste with increasing age (Sergi et al., 2017).
420 The present findings are in line with previous results by Hansen and colleagues (2006) who reported
421 an inverse association between age and the bitter taste of caffeine. Interestingly, the results of our
422 study revealed a systematic decrease in sour/bitter perception in food models with increasing age but
423 only at the highest concentration of the target tastes. Indeed, an age effect was found only in pear
424 juice samples with higher citric acid concentrations, and in the more bitter chocolate pudding samples.
425 Accordingly, recent data by a large sample of Caucasian European subjects demonstrated a significant

426 decrease in taste perception for all five basic tastes, measured in water solutions, with increasing age,
427 and this association was found to be stronger for the higher concentrations especially for bitter and
428 sour (Barragán et al., 2018).

429 No differences in taste perception by women and men in both water solutions and model foods have
430 been here highlighted. The relationship between taste perception and gender yield to mixed literature
431 results (Fischer et al., 2013; Shen et al., 2016, Dinnella et al., 2018) that could be due to several
432 factors, such as the methodology applied to measure taste responsiveness, the food matrix used to
433 elicit different taste perceptions as well as the sample size of subjects involved.

434 Responsiveness to the two target tastes was associated with food liking for the selected food items
435 only in the most responsive consumers. These subjects expressed lower liking for vegetables and fruit
436 juices characterized by high sour/bitter tastes compared to least responsive subjects. Cox et al., (2012)
437 depicted that sensory perception tended to predict liking and intentions to consume brassica
438 vegetables. For example, broccoli hedonics as well as intentions to consume these vegetables were
439 predicted by bitterness perception. Contrarily, recent findings on a large sample size of Finnish adults
440 failed to find a relationship between bitter sensitivity and either vegetable liking or consumption
441 (Puputti et al., 2019). Our results are in line with previous findings showing that perceived bitterness,
442 correlated also with sour taste, of brussels sprouts, kale and asparagus is negatively associated with
443 vegetable preferences (Dinehart et al., 2006) and with findings showing that liking was inversely and
444 significantly associated with perceived bitterness in beverages (grapefruit juice, beer, and scotch;
445 Lanier et al., 2005). Literature data on fruit and vegetable preferences with respect to taste
446 responsiveness is controversial and it has been predominantly investigated through PROP (e.g. Duffy
447 et al., 2010, Bell and Tepper, 2006; Armstrong and Mattes 2008; Kaminski et al., 2000) as general
448 marker of taste responsiveness, as well as chemesthetic sensations (e.g. capsaicin; Nolden et al.,
449 2020).

450 No significant differences among subjects with different taste responsiveness on preference for low
451 bitter/sour foods was found, suggesting that the differences in preference were related to taste stimuli
452 usually associated to warning sensations and something that could be potentially toxic, non-edible as
453 well as unripe fruits and spoiled foods (Laureati et al., 2018). Looking also to the familiarity data, no
454 differences in the scores provided by the two clusters of consumers to the food items considered have
455 been shown. This lack of difference between clusters can be explained by the fact that all the food
456 items included in the questionnaires are usually part of the Mediterranean diet, that is widely adopted
457 in Italy (Predieri et al., 2020).

458 Interestingly, the two clusters tended to differ in the choice for vegetables and fruit juices
459 characterized by intense sour/bitter tastes. In particular, low bitter/sour responsive subjects seem to

460 choose more specific sour/bitter plant-based foods (e.g. chicory and grapefruit juice) compared to the
461 high responsive subjects. These results, even if the differences highlighted are small, corroborated
462 the previous liking findings suggesting that subjects less responsive to sour and bitter taste choose
463 and prefer fruit and vegetables described by these taste qualities. Thus, it could be hypothesized that
464 these subjects may have a diet richer in healthier components, such as phenols.

465

466 **5. Conclusions**

467 In conclusion, the large sample size as well as the several variables considered in the present study
468 help to deepen the knowledge about the role of sour and bitter taste perception associated with
469 consumers' eating behaviour. The present results suggest that the ability to perceive these taste
470 qualities, tested both in water solutions and real foods, is associated with food acceptability, and to a
471 lesser extent with food choice, for specific foods characterized by components that could have a
472 positive health effect. Dietary intake should be further envisaged to understand if the relationship
473 found among sour/bitter taste and food preferences also reflects differences in actual food
474 consumption.

475

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480

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484

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486

487 **Author contributions**

488 CP undertook the analyses and wrote the original draft of the manuscript; CP, EP, SS, CD and EM
489 contributed to plan the analyses; SS and CD contributed to enrich the analysis and to revise the
490 original draft; CP, EP, SS, CD and EM discussed the interpretation of the results; all authors helped
491 with data collection, reviewed and offered critical comments on the manuscript.

492

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