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

Pagliarini, E[1], Proserpio C[1*], Spinelli S[2], Lavelli V[1], Laureati M[1], Arena E[3], Di Monaco R[4], Menghi, L[5,6], Gallina Toschi T[7], Braghieri A[8], Torri L[9], Monteleone E[2], Dinnella C[2]

[1]Department of Food, Environmental and Nutritional Sciences (DeFENS), University of Milan, 20133 Milan, Italy
[2]Department of Agricultural, Food, Environment and Forestry (DAGRI), University of Florence, 50144 Florence, Italy
[3]Dipartimento di Agricoltura, Alimentazione e Ambiente (Di3A), University of Catania, 95123 Catania, Italy
[4]Department of Agriculture Sciences, University of Naples Federico II, 80055 Naples, Italy
[5]Center Agriculture Food Environment (C3A) University of Trento - Edmund Mach Foundation, 38010 San Michele all'Adige (TN), Italy
[6]University of Southern Denmark – Department of Technology and Innovation; Campusvej 55 – Odense – 5230 – Denmark
[7]Department of Agricultural and Food Sciences, Alma Mater Studiorum, University of Bologna, 40126 Bologna, Italy
[8]School of Agricultural, Forestry and Environmental Sciences (SAFE), University of Basilicata, 85100 Potenza, Italy
[9]University of Gastronomic Sciences, Piazza Vittorio Emanuele II, 9, 12042 Pollenzo, Italy

*Correspondence: cristina.proserpio@unimi.it

Abstract

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

well as a positive correlation between the perceived intensity of the two taste stimuli. Subjects characterized by high responsiveness to the two target stimuli were found to give lower liking scores to foods characterized by sour/bitter tastes and tended to choose less sour/bitter foods compared to less responsive subjects.
Thus, food choice for phenol rich plant-based products could be associated with a reduced responsiveness to bitter and sour tastes and a consequent higher acceptance of food products characterized by these taste qualities.

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

1. Introduction

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

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

Despite the positive impact that the vegetable and fruit consumption plays on subjects' health, there is evidence reporting that plant-based diet represents also a more environmentally sustainable choice compared with animal-based diet. Previous research highlighted that, assuming a constant daily calorie intake, the meat-based food system requires more water, land and energy than the plant-based food system (Pimentel & Pimentel, 2003; FAO, 2017). More recently, this assumption has been also corroborated by other research showing that plant-based diets require fewer natural resources and have less impact on the environment compared with diets rich in animal-based products (Ruini et al., 2015; Davis et al., 2016). In particular, the results obtained by Ruini et al. (2015) suggested that the Mediterranean diet may lead to a lower environmental impact compared to diets that are heavily based on daily meat consumption. The actual approaches applied to make the global food system sustainable, such as food waste reduction, are inadequate given the global population growth and the lack of natural non-renewable resources (Béné et al., 2020). "Going back" to plant-based diets seems to be an important alternative for a more sustainable future (Sabate & Soret 2014).

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

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

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

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

2. Material and method

2.1 Participants

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

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

2.2. Sensory stimuli

Tastant solutions

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

Food models

Pear juice (J) and dark chocolate pudding (P) were selected as appropriate food matrices for testing sour and bitter perception in food models (Monteleone et al., 2017). Ingredients and products distributed by large food companies were used in order to obtain a constant composition and to avoid problems associated with products seasonality. Pudding base formulation was prepared by mixing a commercial pudding powder (ingredients: starch, low-fat cocoa, dextrose, salt, aromas; Cameo S.p.A., Dr. Oekter, Bielefeld, Germany) with 40 g of cocoa powder and 1L of water at 40°C. This mixture was heated in microwave at 900W for 6 min and then at 450W for 4 min. The heating was stopped every 2 min to mix the pudding. A commercial pear juice (ingredients: water, Williams pear puree 50%, sugar, flavourings, acidifier: acid citric; antioxidant: ascorbic acid; Santal, Parmalat S.p.A., Milan, Italy) was used for the base juice formulation. Four pear juice and four dark chocolate pudding samples were prepared by adding, respectively, increased concentrations of citric acid (pear juice: J_1=0.5 g/kg; J_2=2.0 g/kg; J_3=4.0 g/kg and J_4=8.0 g/kg) and sucrose (chocolate pudding: P_1=38 g/kg; P_2=83 g/kg; P_3=119 g/kg and P_4=233 g/kg) to base formulations. Tastants concentrations were selected to elicit a variation in the strength of target sensations from weak to strong. Both food models were preliminarily described by a focus group of trained subjects. Pear juice was characterized by sweetness, sourness and pear flavour; chocolate pudding by sweetness, bitterness, chocolate flavour and to a lesser extent by astringency.

2.3. Questionnaires

Food familiarity and stated liking

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

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

Food choice

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

2.4. Sensory evaluations

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

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

Subjects were extensively instructed to treat the ‘‘strongest imaginable sensation” as the most intense sensation they could ever imagine experiencing. To familiarize the participants with the scale anchors, they were asked to recall a variety of remembered sensations from different modalities (Bajec & Pickering, 2008; Kalva et al., 2014; Webb et al., 2015). Examples of oral (e.g. the cold of a cube of ice in the mouth; the pungency from hot chili pepper) and non-oral sensations (e.g. the noise of a plane that is flying low, the pain felt when shutting a finger in a door) were proposed to encourage the discussion. To practice on the use of the gLMS, subjects were asked to rate the intensity of the brightest light they had ever seen on a paper ballot. The criterion to conclude that the subjects correctly used the scale was that their ratings were higher than “very strong” and lower than “the strongest imaginable sensation of any kind”. Ratings out of this range were individually discussed and the correct use of the scale clarified (Dinnella et al., 2018). Despite an extensive training was performed with the subjects involved, a measure from an independent modality (e.g., sound, or sight) to corroborate the correct use of the scale was performed but not recorded in the present study. However, a similar approach using recalled sensations has been used in many studies (Parkinson et al., 2016; Duffy et al., 2019; Yang et al., 2019).

2.4.2. Evaluation session

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

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

2.5. Data analysis

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

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

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

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

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

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

3. Results

3.1. Differences for expected bitterness and sourness among questionnaire items

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

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

Food item		**Bitter**	**Sour**
Vegetables			
	Low bitter/sour		
	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]
	High bitter/sour		
	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]
	p-value	**<0.0001**	**<0.0001**
Fruit juices			
	Low bitter/sour		
	Multivitamin juice	12[a]	55[a]
	Pineapple	11[a]	45[a]
	High bitter/sour		
	Orange juice	29[b]	70[b]
	Grapefruit	75[c]	75[b]
	p-value	**<0.0001**	**<0.0001**

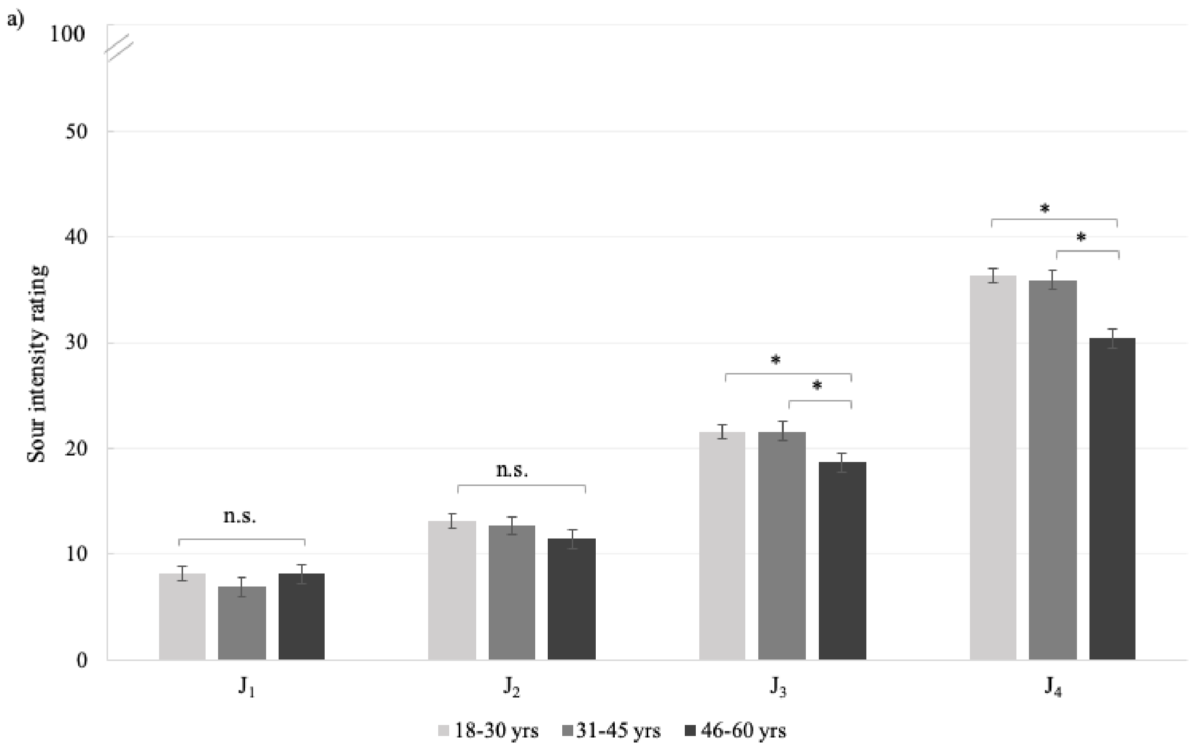
3.2. Taste perception in water solutions and food models

No significant gender effects on sour and bitter perception in water solutions were found. Only weak tendencies have been highlighted for sour and bitter perception according to age ($F_{(2,1192)}$=2.72, p=0.06, η^2= 0.005; $F_{(2,1192)}$=2.21, p=0.11, η^2= 0.004, respectively), with the youngest group of subjects (18-30 years old) that tended to be more responsive compared with subjects aged 31-45 and 46-60 years.

Considering the pear juice and chocolate samples, results revealed a significant effect of the main factor sample ($F_{(3,4768)}$=674.90; p<0.000; η^2= 0.29; $F_{(3,4768)}$=647.73; p<0.0001; η^2= 0.29; respectively). Sour intensity ratings systematically increased from J_1 (7.7 ± 0.4) to J_4 (34.2 ± 0.4) in pear juice samples and bitterness systematically decreased from P_1 (30.0 ± 0.4) to P_4 (6.6 ± 0.4) in chocolate pudding samples. The main factor gender was not significant for sourness and bitterness in model foods.

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

In both model foods the interaction age*samples (**Figure 1a-b**) showed a significant but very small/small effect on sour and bitter responsiveness ($F_{(6,4768)}$=3.66, p<0.001; η^2= 0.005; $F_{(6,4768)}$=9.20, p<0.0001, η^2= 0.01 respectively.). An age effect was found on intensity ratings only in samples where the intensity of target sensations was rated at moderate level or higher. Samples J_3 and J_4 were rated lower in sourness by subjects aged 46 to 60 years than younger (18-30 and 31-45 years), which did not significantly differ from each other. Bitterness intensity decreased with increasing age in sample P_1 and it was rated higher by subjects aged 18-31 years than older (31-45 and 46-60 years), which did not significantly differ from each other. The lack of significant differences due to age in sample J_1 and J_2 and P_3 and P_4 is possibly due to a floor effect induced by the low intensity level of the target sensations in these samples (ranging from weak to less than moderate).



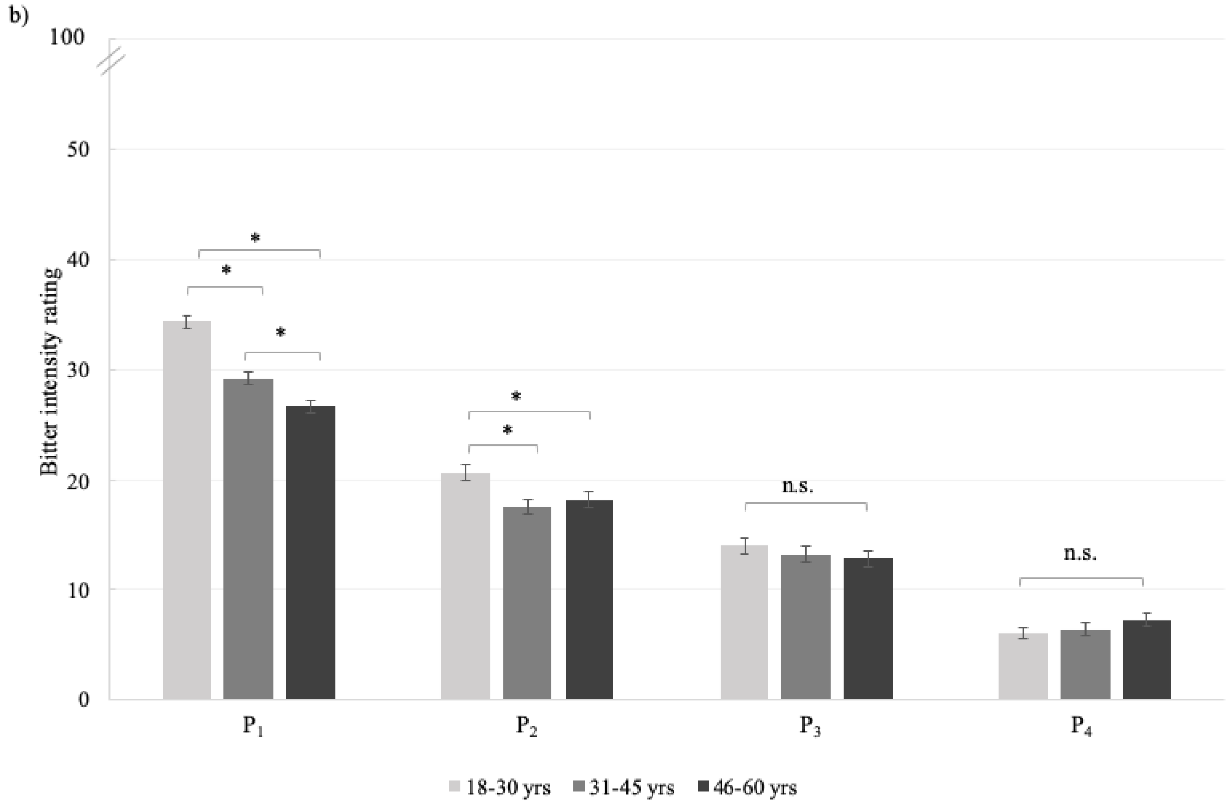


Figure 1a-b. Sour (a) and bitter (b) mean intensity ratings (± SEM) by samples (pear juice samples: J_1 - J_4; chocolate pudding samples: P_1 - P_4) and age groups (18-30; 31-45; 46-60 years old). * p<0.05; n.s. not significant

The interaction age*gender showed a significant but very small effect ($F_{(2,4768)}$=4.06, p<0.05; η^2= 0.002) only on sour intensity ratings. In particular, among subjects of 31-45 years, men gave significant lower intensity ratings (18.4 ± 0.6) compared to women (20.2 ± 0.5), while no gender differences were found in the other age groups (group 1 and group 3). The interaction gender*sample was significant ($F_{(3,4768)}$=3.02, p<0.05; η^2= 0.002) only on bitter intensity ratings. Gender-related differences have been found only for sample P_1 which was perceived as more bitter by women (31.0 ± 0.5) compared to men (29.1 ± 0.6). The other interactions were not significant.

Pearson correlations coefficients (**Table 2)** highlighted a significant positive correlation among sour intensity perceived in water solution and in pear juice samples. The correlation became stronger with the increasing amount of citric acid in the pear juice. A significant positive correlation was also found between bitter intensity perceived in water solution and in chocolate pudding samples. The correlation became weaker with the increasing amount of sucrose as the intensity of the bitterness decreased. Moreover, bitter and sour perception were always weakly but positively correlated to each other both in water solution and food models. For example, the sourness perception in samples J_4 with the higher amount of citric acid was significantly and positively correlated with the bitterness perception in the chocolate pudding sample with the lower amount of sugar P_1 (most bitter). Pearson correlations performed with consumers split according to the three-age groups revealed similar results (see supplementary material).

Table 2. Pearson correlation coefficients among taste perception (S= sour, B=bitter) in water solution and model foods (pear juice with increasing citric acid: J_1=0.5 g/kg; J_2=2.0 g/kg; J_3=4.0 g/kg and J_4=8.0 g/kg; Chocolate pudding with increasing sugar: P_1=38 g/kg; P_2=83 g/kg; P_3=119 g/kg and P_4=233 g/kg)

	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

All values are significant at p <0.01

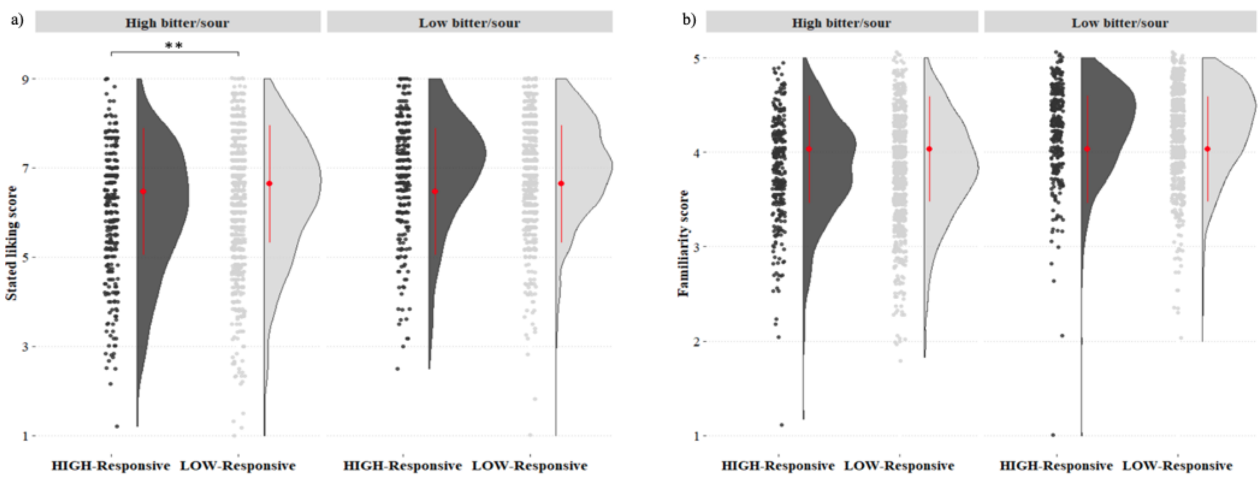
3.3 Consumers segmentation according to sour and bitter taste responsiveness

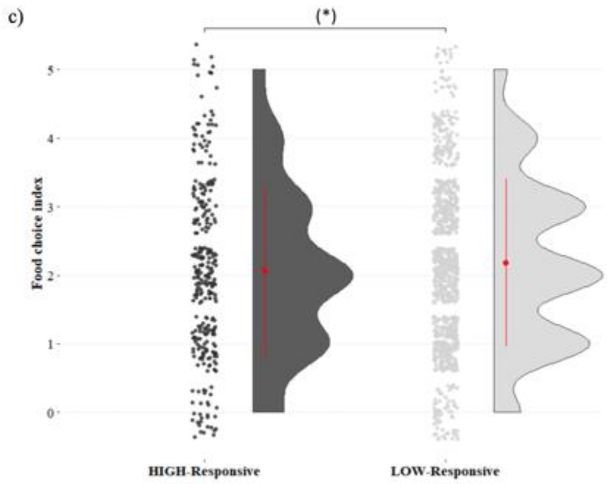
Sour and bitter intensity in water were used as a general index to classify subjects according to their responsiveness to target tastes. Two clusters were identified showing significant differences in sour ($F_{(1,1196)}$=1456.46; p<0.000; η^2=0.55) and bitterness perception ($F_{(1,1196)}$=418.71; p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

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

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

Clusters significantly differed in liking scores for *High bitter/sour* vegetables and fruit juices ($F_{(1:1193)}=10.19$; $p<0.001$; $\eta2=0.06$) **(Figure 2a).** Consumers more responsive to these target tastes (*HIGH_Responsive*) gave significant lower liking scores to *High bitter/sour* vegetables and fruit juices (6.0 ± 0.08) compared to less responsive subjects (*LOW_Responsive*, 6.3 ± 0.05). No significant differences between clusters were observed for liking scores for *Low bitter/sour* group ($F_{(1:1193)}= 0.52$; $p=0.47$). Familiarity scores for both *High* and *Low bitter/sour* items were not significantly different by cluster (*High bitter/sour*: $F_{(1:1188)}=0.02$; $p=0.89$; *Low bitter/sour*: $F_{(1:1188)}=0.67$; $p=0.80$) (**Figure 2b**). Clusters tended to differ in food choice score ($p<0.10$) with *HIGH_Responsive* subjects showing a lower choice for *High bitter/sour* food (2.0 ± 0.07) compared to *LOW_Responsive* subjects (2.2 ± 0.04) **(Figure 2c).** Results split according to the three-age groups revealed that the differences in eating behavioural variables by clusters were mainly associated with subjects aged 18-30 years (see supplementary material).





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

4. Discussion

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

The present results highlighted a weak but significant positive correlation between the perception of sour and bitter tastes in water solutions. In this vein, Cattaneo and colleagues (2019), have recently reported a positive correlation between sour and bitter thresholds in a small group of healthy adults. Moreover, clusters based on tastant solution perception (more sensitive, semi-sensitive, and less sensitive tasters) have been identified by Puputti et al., 2018 involving a large population sample. The authors highlighted that the membership in a taste cluster could be partially forecasted by the sensitivity to other taste modalities. This correlation among tastes mediated by different mechanisms, G-coupled protein receptors for bitter and ion channels for sour (Drayna, 2005), could be explained by a dichotomy in taste coding for pleasant compounds, such as sweet and savoury, versus those perceived as dangerous, such as sour and bitter stimuli (Hladik et al., 2002). It could be questioned that the correlations here highlighted could be due to the well-established sour-bitter confusion (Robinson, 1970; Gregson & Baker, 1973). However, prior to tasting, extensive instructions were provided by the experimenters to the subjects to avoid this misperception. Moreover, in this study sourness and bitterness were evaluated in different food samples (the former on pear juices and the latter on chocolate puddings). It is also worth considering that sourness was evaluated for a pure stimulus in water and for a fruit juice added with citric acid. The intensity of sourness in fruit juice significantly increases with citric acid concentration (see fig. 1a) thus it is reasonable to assume that ratings refer to sour taste and not to bitter taste. Bitterness was rated in a water solution of a pure stimulus and in chocolate added with increasing amount of sugar. Bitterness regularly decreases as effect of suppression by sweetness (see fig. 1b). All these considerations make unlikely the confusion between the two sensations.

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

Looking to age effects on bitter and sour responsiveness older subjects (46-60 years old) tended to give lower intensity rating scores in water solutions compared to younger subjects. This tendency was found to become significant, although the effect size was always small, considering bitter and sour perception in food models. These results are supported by previous evidence reporting a decline in the gustatory function, mainly investigated using aqueous solutions, in the older population that could be due to several factors, including physiological changes such as a taste receptor cells dysfunction (Methven et al., 2012). Even if evidence about the extent and type of taste loss with aging, sour and bitter tastes seem to be the most affected taste with increasing age (Sergi et al., 2017). The present findings are in line with previous results by Hansen and colleagues (2006) who reported an inverse association between age and the bitter taste of caffeine. Interestingly, the results of our study revealed a systematic decrease in sour/bitter perception in food models with increasing age but only at the highest concentration of the target tastes. Indeed, an age effect was found only in pear juice samples with higher citric acid concentrations, and in the more bitter chocolate pudding samples. Accordingly, recent data by a large sample of Caucasian European subjects demonstrated a significant decrease in taste perception for all five basic tastes, measured in water solutions, with increasing age, and this association was found to be stronger for the higher concentrations especially for bitter and sour (Barragán et al., 2018).

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

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

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

Interestingly, the two clusters tended to differ in the choice for vegetables and fruit juices characterized by intense sour/bitter tastes. In particular, low bitter/sour responsive subjects seem to choose more specific sour/bitter plant-based foods (e.g. chicory and grapefruit juice) compared to the high responsive subjects. These results, even if the differences highlighted are small, corroborated the previous liking findings suggesting that subjects less responsive to sour and bitter taste choose and prefer fruit and vegetables described by these taste qualities. Thus, it could be hypothesized that these subjects may have a diet richer in healthier components, such as phenols.

5. Conclusions

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

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Author contributions

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

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