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The nature and origins of crossmodal associations to astringent solutions and basic tastes

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ABSTRACT

People match gustatory (basic tastes) and non-gustatory stimuli (e.g., colors, shapes, and textures) to each other in a reliable manner. Yet, whether other attributes of the experience of flavor, such as, for example, astringency also evidence such reliable crossmodal mappings is currently unknown. Therefore, the aim of this study was to assess whether individuals make reliable crossmodal mappings between astringent solutions and non-gustatory stimuli (e.g., colors, shapes, hand-felt roughness/smoothness), and to examine the basis of any mappings observed. Participants sampled 6 solutions – astringent and 5 basic tastants – at 2 concentrations each (low, high), and for each selected their best matching color, texture, and shape (in three separate counterbalanced blocks). After making their selections, the participants evaluated the valence of the solutions, their colors, textures, and shapes, as well as the qualities/intensities of the solutions, and their confidence in the matches they made. Participants reported the rationale for their color-, texture- and shape matches at the end of the study. Color, texture, and shape selections evidenced consensual mappings, and participants were generally confident in all matches to a comparable level. Whilst people typically reported that their color matches were driven by real world associations (e.g., yellow chosen for sour, as lemons are yellow and sour), followed by valence (liking; e.g., pink for sweet, as both are liked), texture and shape matches to solutions were more attributable to intensity (e.g., rougher textures, selected for rougher feeling [e.g., astringent] solutions) as well as valence. Implications for flavor binding and marketing are discussed.

1. Introduction

When asked, people naturally pair gustatory stimuli (e.g., basic tastes) with non-gustatory stimuli (e.g., colors, shapes, textures) in a surprisingly reliable manner to each other (Di Stefano & Spence, 2022; Motoki, Marks, & Velasco, 2023; Motoki, Spence, & Velasco, 2023; Spence et al., 2015; Spence & Levitan, 2022; Velasco, Woods, Petit, et al., 2016). For instance, people have been reported to associate sweet tastes with pink colors, round shapes, and smooth textures (Pistolas & Wagemans, 2023; Saluja & Stevenson, 2018; Spence, 2023; Velasco, Woods, Liu, & Spence, 2016; Velasco, Woods, Petit, et al., 2016). These mappings are examples of crossmodal correspondences (CMCs; aka crossmodal mappings) – i.e., the reliable pairings individuals form between two sensory features. CMCs are widely studied in the chemical senses due to their relevance in understanding sensory associations, and in turn interactions, as in flavor perception (Spence, 2011; Stevenson, 2009). Yet, beyond the basic tastes, there has been remarkably little research assessing CMCs to other oral-sensations that are pertinent to the experience of flavor. One such sensation is astringency. It is defined as an oral somatosensory sensation that is characterized by a drying, puckering, and rough mouthfeel, experienced during eating of several widely consumed tannin-rich foods/drinks (e.g., wines, over stewed black tea, dark chocolate, coffee; Gawel et al., 2000; Green, 1993; Vidal et al., 2015; Zhu et al., 2023). As such, this study examines if individuals

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reliably pair non-gustatory stimuli (i.e., shapes, colors, hand-felt roughness/smoothness) to oral sensations of astringency and to basic tastes, some of which also have an astringent component. In addition, the mechanistic basis of these mappings is explored.

Individuals reliably pair visual features – colors and shapes – to the basic tastes (Motoki, Marks, & Velasco, 2023; Motoki, Spence, & Velasco, 2023). Color-taste CMCs have been studied extensively, with a number of common CMCs emerging: sweet tastes to pink/red, salty to blue/white, sour to yellow/green, bitter to dark greens/black/browns, and – albeit studied to a lesser extent – umami to reddish-orangey-browns (Ikeda, 2002; Koch & Koch, 2003; O'Mahony, 1983; Saluja & Stevenson, 2018; Tomasik-Krótki & Strojny, 2008; Woods et al., 2016; Woods & Spence, 2016). Beyond the basic tastes, associations between the color red and piquancy (spiciness) have also been reported (Ho et al., 2014; Shermer & Levitan, 2014; Spence, 2019) – providing preliminary support for the existence of oral-somatosensory and color mappings. Shape properties (e.g., angularity vs. curvilinearity) too appear reliably paired to basic tastes (Spence & Levitan, 2022; Spence, 2023). Individuals tend to associate sweetness to roundness, and other basic tastes – i.e., bitter, sour, salty, and umami, with more angular shapes (e.g., Motoki, Marks, & Velasco, 2023; Motoki, Spence, & Velasco, 2023; Velasco, Woods, Liu, & Spence, 2016; Velasco, Woods, Petit, et al., 2016).

In addition to visual features, there has also been some research concerning mappings between textures (such as roughness/smoothness) and basic tastes. These studies suggest basic tastes may be reliably associated with roughness/smoothness. Sweet and umami appear to be associated with smooth (or silky/slippery) hand feel, smooth visual, and smooth verbal descriptors of texture – suggesting these tastes may be associated with smooth textures (Barbosa Escobar & Wang, 2023; Riofrio-Grijalva et al., 2020; Spence & Ngo, 2012). Sour, salty, and bitter tastes/taste words are mapped to more rough and sandy textures (Escobar et al., 2022; Riofrio-Grijalva et al., 2020). In terms of astringency, the perceived flavor profile of astringent beverages (wine, coffee) appears shaped by hand-felt texture (e.g., roughness of the cup; Wang & Spence, 2018; Carvalho et al., 2020; see also Biggs et al., 2016; Piqueras-Fiszman & Spence, 2012). For example, Carvalho et al. (2020) reported that a rough (vs. smooth) cup increased the perceived aftertaste of coffee (how dry the mouth felt post consuming the coffee), in both coffee experts and amateurs. While these latter studies are exemplars of cross-modal interactions (i.e., how two sensory features may interact and bias each other's percept), and not crossmodal mappings per se, they nevertheless suggest that astringency may be reliably associated with hand-felt roughness/smoothness.

In addition to their limited assessment of oral-somatosensory features (such as astringency), the majority of crossmodal studies in gustation have relied on taste words/descriptors – i.e., very few studies have examined whether gustatory and non-gustatory (color, shape, texture) mappings exist when using real tastants. For example, only one study appears to have examined crossmodal mappings made between real tastants and colors (Saluja & Stevenson, 2018), and between roughness and basic taste mappings (Riofrio-Grijalva et al., 2020). Similarly, taste and texture mappings have predominantly relied on visual or texture *words*. Hand-felt textures have only been used in one study assessing taste-texture CMCs (Riofrio-Grijalva et al., 2020) – and here, stimuli used were multi-textured (e.g., varied on roughness/smoothness, softness, and slipperiness etc.) – meaning it is unclear if individuals were pairing tastes to textures in isolation or in combination with one another (e.g., was sweet paired to smooth hand-felt textures, or was it smooth *and* soft stimuli?).

While convenient – as they do not rely on physical stimuli and can thus be conducted outside of the laboratory (Lee & Spence, 2022) – reliance on words for taste or texture stimuli has some potential limitations. First, the taste and texture stimuli evoked by a word are rarely standardized – i.e., asking someone to pair *sweet* to a color, may bring to mind fairy floss to one individual (a high intensity sweet stimulus) or sweet potato to another (a mildly intense sweet stimulus). A similar issue exists with the word *smooth* (e.g., it could bring to mind satin to one person and cat's hair to another). These associated stimuli are different, and so too then may be the CMCs made to them. Second, certain taste words may be misunderstood for one another, or not readily understood. This is particularly so for sour and bitter – which are sometimes confused (O'Mahony et al., 1979). It is possible that the sour-bitter confusion is learnt, as sour foods/drinks are often described as bitter (e.g., bitter lemon; O'Mahony et al., 1979), or because these qualities co-occur in food. Similarly, the word astringency appears to be poorly understood amongst consumers, meaning that reliable verbal mappings may be harder here (Fleming, 2015).

Another related issue of using taste/texture words (and visual textures), is that these stimuli limit assessment of mechanism – namely, an understanding of what is driving the reported crossmodal pairings. Three non-exclusive explanations have been advanced for CMCs (Spence, 2011). First, the statistical account suggests that through environmental exposure individuals learn contingencies between the properties of objects (e.g., rock-salt is white, hard, and angular; Di Stefano & Spence, 2023). In other words, crossmodal associations are learnt from the common associations found between two sensory stimuli in the real world – termed real world associations in this manuscript.

Second, semantic accounts suggest that CMCs arise from common verbal descriptors across sensory continua (i.e., shared meanings; Marks, 1975). This is evident in common linguistic terms used across modalities, such as describing both shapes and flavours as "rounded" or referring to "notes" in both odours and music (Cytowic, 2003). One form of shared meaning may relate to affective or emotional valence (Palmer et al., 2013), consistent with Osgood et al.'s (1957) work which identified pleasantness as common across all sensory continua. Given that both tastes/colors/shapes/textures reliably vary in reported valence (e.g., Palmer & Schloss, 2010), it may be reasonable to expect that CMCs here are influenced by this shared emotional quality (Velasco, Woods, Liu, & Spence, 2016; Velasco, Woods, Petit, et al., 2016). Relatedly, several researchers find that similarities in pleasantness/ liking between sensory continua, at least partially, underly CMCs (Saluja & Stevenson, 2018; Stevenson et al., 2012) - with this explanation often referred to as the valence account (Spence, 2011).

The third explanation for CMCs, is the structural explanation, which suggests that properties of stimuli common across the senses (e.g., size, duration, intensity) may be associated together due to common neural coding of these key perceptual features (Stevens, 1957). For example, people pair more saturated (intense) colors to more concentrated tastes (i.e., high vs. low concentrated tastes; Saluja & Stevenson, 2018). While the structural account may not be used to determine the *qualitative* nature of mappings (e.g., what color is associated to a solution), they may be important in determining the *quantitative* nature of mappings – i.e., the intensity of the stimuli selected. Importantly, these accounts – especially the structural account – can therefore only be tested when using solutions that vary in terms of their intensity (or concentration), and not descriptors (i.e., taste/solution words).

In the study reported here, we examine crossmodal mappings between astringent and basic taste solutions to non-gustatory stimuli (colors, shapes and textures), and the basis of these mappings. To achieve this goal, participants were asked to sample (swill and spit), 6 solutions (astringent solutions and 5 basic tastants), at two concentrations (low, high) – three times, each in a separate block. In the first block, participants sampled a solution and then picked a color (or white/black/Gy) using a color wheel – rating the solutions on perceived taste properties, liking and intensity, and color on liking. In the second block, participants picked a hand-felt texture), that varied only on smoothness/roughness (i.e., 5 sandpaper grits, ranging from very smooth to very rough), rating the texture on perceived roughness and liking. In the third block, participants picked a shape (out of eight possible), varying in angularity, symmetry and complexity – and rated the shape on liking. Block order was counterbalanced across participants. At the end of the experiment, participants were asked to match solution names to color/texture/shape names, and to report the rationale for their mappings.

2. Method

2.1. Participants

Fifty undergraduate students (43 females and 7 males) at Macquarie University, took part in the study in exchange for course credit. Sample size was calculated using Howell's (2010) effect size formula, with effect sizes in these formulas based off past taste- and color/shape/texture CMC studies (Pistolas & Wagemans, 2023; Saluja & Stevenson, 2018; see Supplementary Materials, for full power analysis). All participants were aged between 17 and 46 years old ($M = 19.8$, $SD = 4.4$). All participants consented to take part in the current study, which they were informed examined the associations between colors, textures, shapes and tastes. Participants reported feeling well (not sick), and having normal chemosensory (smell, taste) and tactile function, as well as normal color vision (based version of the Ishihara color vision test; see Section 2.2.1 below). Ethics was approved by the Macquarie University Human Research Ethics Committee (520241685255953), dated March 15th, 2024.

2.2. Materials and measures

2.2.1. Ishihara color vision test

Participants were provided with a 12-item web-based version of the Ishihara Color Vision Test to assess for color vision deficiency. All participants received 100 % in this test (indicative of normal color vision).

2.2.2. Chemosensory questionnaire

A 12-item self-report questionnaire was used to screen for impairments in the chemical senses (i.e., gustation, olfaction and the trigeminal system). Participants specified if they had current sickness or nasal congestion; previous or current presence of nasal allergies, sinusitis and olfactory or taste problems; whether they had/previously had a nasal or facial surgery, or a face related accident or injury; whether been knocked unconscious, as well as their current/previous smoking status. If a participant responded yes it was coded as '1', unsure '0.5' and no '0' – thus total scores could range from 0 to 12, with 12 indicative of greater self-reported chemosensory impairment. No participant had scores indicative of chemosensory impairment ($M = 1.01$, $SD = 1$, range 0 to 4.5).

2.2.3. Preparation of solutions

Solutions were prepared at a low and high concentration, as based off previous studies (Wang et al., 2016; Saluja & Stevenson, 2018; Lawless et al., 1994). All solvents were dissolved in water and were as follows: sucrose (sweet; Black & Gold; Australia), citric acid (sour; Sigma; Austria), sodium chloride (salty; Woolworths; Australia), monosodium glutamate (MSG; meaty; Ajinomoto; Japan), quinine (bitter; Aldrich; Germany) and tannic acid (astringent; Vintner's Harvest; New Zealand; see Table 1). All the solutions were colorless and odorless, except for tannic acid which had a pale red color and a faint smell. As such, people were asked to sample all solutions with their eyes closed and nose pinched to reduce any olfactory/visual cues from biasing mappings. As in previous studies (e.g., Saluja & Stevenson, 2018), the solutions were replaced every five days to ensure they were safe to consume.

Table 1
Mass of each solution in g/L of water, at low and high concentrations.

Solution	Solvent used	Stimuli type	Concentration	
			Low	High
Sweet	Sucrose	Tastant	25 g/L	100 g/L
Sour	Citric acid	Tastant	0.6 g/L	2 g/L
Salty	Sodium chloride	Tastant	3 g/L	10 g/L
Meaty	MSG	Tastant	3 g/L	45 g/L
Bitter	Quinine HCl*	Tastant	0.02 g/L	0.16 g/L
Astringent	Tannic acid	Oral-somatosensory	0.08 g/L	4 g/L

* For both quinine solutions, 1 mL of propylene glycol was used to aid dissolving.

2.2.4. PowerPoint slides

Participants recorded their color choice for each solution using Microsoft PowerPoint, through a 19-page PowerPoint presentation. Each slide contained a box that the participant was asked to fill with any color using a standard computer hue saturation value (HSV) color wheel on PowerPoint. Participants were instructed to adjust their color choice as needed using the brightness slider scale located on the right side of the wheel. Together, the wheel and brightness scale provided a measure of color choice (hue), intensity (saturation) and luminance (brightness) for each solution.

2.2.5. Color classification

Participants' color sections from the HSV color wheel were classified into 7 categories (orange/brown, yellow, green, blue, purple, pink/red, monochrome [grey/black/white]), based on previous research (Saluja & Stevenson, 2018). This involved two steps. First, for each selection, hue, saturation and luminance values were extracted. Second, color selections were categorized using hue degree, as follows: hue degrees from 16°-30° were classified as orange/brown, 31°-76° as yellow, 77°-149° as green, 150°- 269° as blue, 270°-285 as purple and 286°-15° as pink/red. For monochrome choices, colors were based off luminance values – i.e., white (luminance >99), grey (2–95), or black (<2).

2.2.6. Sandpaper gratings

Five sandpaper gratings were used in this study, which corresponded to different levels of roughness and smoothness. These gratings were: 1500 grit (very smooth), 800 grit (smooth), 180 grit (moderately smooth/rough), 80 grit (rough), 40 grit (very rough). All gratings were cut into a rectangular piece measuring 8 × 19 cm and placed adjacent to each other (i.e., side by side) on a plastic tray. These sandpaper swatches were checked regularly and did not require replacing throughout the experiment.

2.2.7. Shapes

Eight shapes, commonly used in CMC shape research (Velasco, Woods, Liu, & Spence, 2016; Velasco, Woods, Petit, et al., 2016) – which varied in symmetry, complexity and angularity - were presented visually (on a computer) to participants (see Fig. 1). Participants had to select one shape per solution.

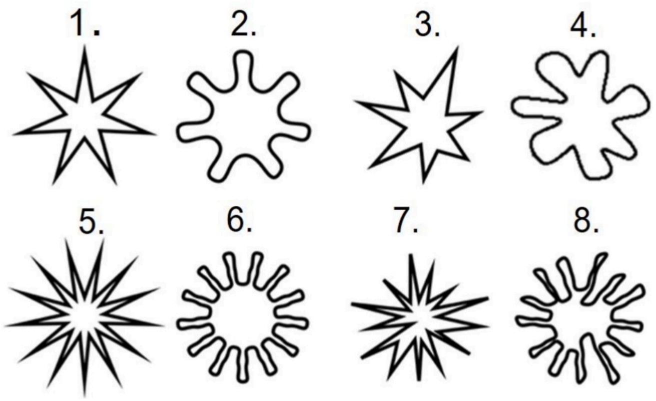

Fig. 1. Eight shapes used for shape-solution mappings.

2.2.8. Rating scales

2.2.8.1. Taste quality rating scales. Participants rated how intense, irritating, sweet, sour, salty, bitter, meaty and metallic they found each solution, on separate linear scales ranging from ‘not at all’ (0) to ‘very’ (100). As data on the solutions’ metallic properties were not related to the aims of this manuscript, these data were not analyzed.

2.2.8.2. Solution liking rating scale. Participants rated how much they liked/disliked each solution on a bipolar continuous scale, which ranged from ‘dislike very much’ (−50) to ‘like very much’ (50), with a label ‘neither like or dislike’ (0) positioned at the center of the scale.

2.2.8.3. Oral-somatosensory rating scales. Participants made four ratings to measure the oral somatosensory (tactile) properties of each solution. Namely, participants rated (1) how astringent the solution was – which was defined to all participants, as the feeling as though saliva was drawn from their mouth; (2) how much their mouth puckered from the solution – with the experimenter visually demonstrating what a mouth pucker was (as based off Ekman and Freisen’s (1976) facial action unit images); (3) how rough their mouth felt from the solution they sampled; and (4) how dry their mouth felt from the solution they sampled. Each rating was made on separate continuous scales, ranging from ‘not at all’ (0) to ‘very’ (100). In addition to these four scales, participants were asked to describe, in a free text box, if the solution they had sampled caused any other sensations in their mouth, with the options ‘Yes (please describe briefly)’.

2.2.8.4. Color, texture and shape liking rating scales. Participants rated how much they like the color, texture and shape they selected on separate linear scales. These ratings were akin to the taste liking scale ranging from ‘dislike very much’ (−50) to ‘like very much’ (50), with a label ‘neither like nor dislike’ (0) positioned at the center.

2.2.8.5. Confidence in match ratings. For every mapping (color-, texture-, shape- match made to each solution), participants were asked to rate how confident they felt about the match they made. This confidence in match rating was on a linear scale ranging from ‘not at all’ (0) to ‘very’ (100).

2.2.9. Synesthesia check

Participants were asked to report if they had any unusual sensory experiences (i.e., to check for synesthesia). None of the participants reported having unusual sensory experiences.

2.2.10. CMC rationale

At the end of the experiment, and for each type of mapping (i.e., color-, texture-, shape- solution), participants were asked to explain, with as much detail as possible, why they selected the shapes, textures and colors they did for the solutions, via three separate open-ended text entry boxes (e.g., for textures, *“Please explain the reason for your texture and taste matches today, that is why did you pick the textures you did for the samples you tasted”*).

3. Procedure

All participants attended a lab session for approximately 90 min. Twenty-four hours prior to their session, each participant was sent a reminder email, requesting that they refrain from chewing gum, smoking, vaping, and consuming any food or beverages (except water) 60 mins prior to the session. Upon arrival, participants were asked whether they consented to an experiment which assessed the relationship between tastes, colors, textures and shapes – and all participants did. No participant reported feeling sick, and none reported consuming food or beverages (except water) in the last hour.

Following consent, the trial phase began. A trial phase was done to ensure procedural understanding for the main experiment, given the experiment was lengthy and comprised of multiple steps. This trial phase consisted of five steps. First, participants were asked to close their eyes and pinch their nose – so to avoid visual and olfactory cues from biasing mappings. Second, the experimenter handed the participant a small sample of water (in a 30 mL clear cup) into their hand – and asked the participant to pour this sample into their mouth, and to swill and then spit it into the spittoon (which was positioned within arm’s reach, on the participant’s right side). Third, the participants were encouraged to keep their eyes closed whilst expectorating the solution, and if needed, to bring the spittoon closer to them (e.g., place it on their lap) for expectoration. Fourth, participants were asked to *either* – depending on what counterbalance sequence they were randomly allotted to – pick a color (with eyes open), shape (with eyes open) or texture (with their eyes closed) that best matched the sampled solution. For the color selections, participants were given a Hue-Saturation-Value color wheel and asked to color a square (on a Powerpoint presentation), that best matched their tasting experience. For shape-mappings, participants were shown all 8 shapes, on an online questionnaire and asked to select which shape best (i.e., most naturally) matched the taste (solution) they had sampled, with no further guidance given so as not to bias participants. For texture selections, participants were asked to keep their eyes closed and were presented five hand-felt sandpapers (placed side by side on a tray), that varied in grits (from very smooth to very rough; see Materials), and were asked to glide their fingers across the sandpaper-grits, and specify verbally which best matched their tasting experience. Fifth, participants were given a computerized questionnaire, and asked to rate the trialsample on perceived properties (i.e., basic taste properties, intensity, oral-somatosensory, liking), and the color/texture/shape in their corresponding sections, on liking and confidence in the match (see Materials). After all the ratings were completed, participants rinsed their mouth and the experimental phase began.

The experimental phase paralleled the trial phase and consisted of three parts. In the first part, participants (with their eyes closed and noses pinched) were handed 14 solutions one at a time (i.e., basic tastes and astringent solutions at low and high concentrations +2 water controls). Each participant received the solutions in a unique randomised order. While solutions were randomised, the same randomised order was used in each block (i.e., solutions were presented in the same randomised order for color, texture and shape selections). Block order was counterbalanced across participants. For each solution they had to pick either a color, shape or texture (depending on their counterbalance sequence) - as in the trial phase. In this first part, only, participants were asked to rate the solution on its perceived properties (i.e., taste-, intensity, oral-somatosensory, liking). The color/shape/texture were also rated on liking and confidence in match. In between each solution, participants rinsed their mouth with water, until their palette was cleansed. The second and third part of the experimental phase was the same as part one, with one notable difference. Namely, participants only rated the matched attributes (color/shape/or texture) on their properties (i.e., liking, roughness [texture only] and confidence in match), as solutions were rated on their perceived properties in part one.

After completing the experimental phase, participants were asked to provide a rationale for their matches (i.e., to explain in three separate questions, why they picked the [1] shapes, [2] colors, and [3] textures that they did), to complete a basic chemosensory functioning questionnaire and a synesthesia check. This concluded the experimental session.

4. Analysis

4.1. Solution properties

4.1.1. Taste quality

To confirm that participants could correctly identify each tastant’s primary quality, a target minus non-target score was calculated for each tastant at each concentration step. First, the average of all of the non-target taste qualities for each tastant was calculated (e.g., for sucrose; saltiness, sourness, bitterness, and meatiness ratings were averaged). Second, this average non-target score was then subtracted from the nominal target quality (e.g., for sucrose–sweetness), before being compared to a mu of 0. Alpha was set at 0.017 for each tastant type, following Bonferroni correction by concentration level (i.e., 0.05/2).

4.1.2. Astringency quality

To confirm that participants perceived tannic acid as more astringent than other solutions (i.e., the basic tastants – and noting that some of these can have astringent properties), a target minus non-target astringency score was calculated at each concentration step. First, a total astringency score was made by summing the oral-somatosensory ratings (i.e., how much the mouth puckered, how dry the mouth felt, how rough the mouth felt, and how astringent the solution was) for each solution. Second, this total astringency score, was averaged for all of the non-target solutions (basic tastants), at each concentration step. Third, and at each concentration step, this average non-target score was then subtracted from the target (tannic acid's) solution's total astringency score, before being compared to a mu of 0.

4.2. Color, texture, and shape selections in response to the solutions

To assess the consistency of color, texture and shape pairings with astringent/taste solutions, between participants, chi-square tests of independence were used. While separate analyses were run for each type of solution CMC (i.e., color, texture and shape), the same approach described next was adopted. First, the null hypothesis is that responses are equally distributed across the sub-categories. As such, an expected (chance) value was calculated by dividing the number of participants ($n = 50$), by the number of sub-attributes in a given attribute (i.e., 7 colors [yellow, green, blue, pink/red, orange/brown, grey/white/black], 5 sandpapers [1500 grit [very smooth], 800 grit [smooth], 180 [moderately smooth/rough], 80 [rough], 40 [very rough]) and 8 shapes [see Fig. 1]). For example, the expected value for solution-texture mappings, would be 10 (i.e., 50/5 grits). Second, and to ensure independence (each person only contributed a single color−/texture−/shape- match for a given solution), 12 chi-square tests (i.e., 6 solutions × 2 concentrations) were run for each type of CMC, with alpha family-wise adjusted by solution type (0.05/6). Third, in each chi-square analysis, the observed frequency (i.e., the number of participants who selected a given color/texture/shape for a solution) was compared to the expected frequency (i.e., the number of participants, that *by chance* would select a given color/texture shape). This determined whether the mappings made were due to chance (i.e., null hypothesis) or significantly greater than chance.

Finally, post-hoc chi-square tests were used to explore the source of significant effects. In these post-hoc tests, the number of people who selected the modal (most selected) color/shape/texture sub-attribute of interest (e.g., pink for sweet) was compared to the total number of people who selected the remaining sub-attributes (e.g., number of people who selected yellow, green, blue, orange/brown, grey/white/black for sweet). Expected values were adjusted accordingly (e.g., For the color matches, the expected value of the target sub-attribute would equal 1/7 colors × 50 [7.1] vs. the sum of all remaining sub-attributes expected = 6/7 colors × 50 [42.9]).

4.3. Mechanistic basis of CMCs

4.3.1. Valence account

The aim of this analysis was to explore the role of the valence account in each CMC (color-, texture-, and shape- solution). For each type of solution mapping (color, texture, or shape), a *t*-test was run comparing the standardized correlation between solution-liking and color-, texture-, and shape-liking against a mu of zero (indicating no correlation).

4.3.2. Intensity mediation

To evaluate the impact of solution concentration on color-intensity (saturation of the selected colors), and roughness-intensity (perceived roughness of the selected sandpapers), Repeated Measures-ANOVA (RM-ANOVAs) were run on these data separately. For each RM-ANOVA (i.e., color intensity RM-ANOVA, and perceived roughness RM-ANOVA), there were two factors: (1) solution type (sweet, sour, salty, bitter, meaty, astringent) and concentration (low, high). The intensity account could not be assessed via quantitative statistics for shape-solution mappings, as there was no linear measure of shape intensity. As such, the role of the intensity-based account in shape mappings is determined qualitatively, via analysis of participants' rationales (see 3.4.3 below).

4.3.3. Participants' rationale for their CMCs

Participants' rationales provided for their color-, texture- and shape-solution CMCs were classified into four non-mutually exclusive accounts: (1) Real world associations; (2) Valence; (3) intensity matching; and/or (4) other (e.g., innate, ambiguous). Notably, as these were non-mutually exclusive, participants could have their responses coded into multiple categories (e.g., a match could be driven by real world associations, as well as valence). For each type of CMC, the proportion of participants who selected a given category, and exemplar responses are reported.

4.3.4. Confidence in match

To assess if participants were more confident of certain CMCs over others, confidence in match scores were aggregated across solutions by CMC type – leading to three aggregate confidence in match scores (i.e., a color-, texture-, and shape- solution confidence in match score). A one way RM-ANOVA with factors Mapping-Type (color-, texture-, shape-solution), were run on these confidence in match ratings.

5. Results

5.1. Solution properties

5.1.1. Taste quality

Results in Table 2 indicate that for each tastant, the target taste quality was the primary perceived taste quality. As such, all values are positive, with mean differences averaging approximately one-third of the rating scale.

5.1.2. Astringency quality

A target non-target analysis was run to assess if tannic acid was perceived, on average as more astringent than the basic tastes. Whilst high-tannic acid ($M = 39.2$, $SD = 65.1$), had significantly higher total astringency scores than the basic tastants ($Z = 3.91$, $p < .001$), the basic tastants were, on average, more astringent ($M = -10$, $SD = 53.3$) than low tannic acid ($Z = -2.27$, $p = .023$). In only a substantial minority of the sample (i.e., 32 %, $N = 16$), was the non-target minus target score for low tannic acid greater than 0. Thus, for the majority of the sample low tannic acid was not perceived as significantly more astringent than the other basic tastes.

5.2. Color, texture, and shape selections to the solutions

Color-, texture-, and shape- solution selections to each solution are detailed separately below. A summary figure, showing the prototypical colored and textured shape for each solution can be found in Fig. 3.

5.2.1. Color solution Chi Square tests

For almost all solutions – barring low tannic (astringent) and low MSG (meaty/umami) – participants' color selections were non-random (after adjusting alpha, 0.05/7; See Fig. 2). The most common color chosen for each solution was as follows: red/pink for sucrose (sweet), blue for NaCl (salty), green for citric acid (sour), orange/brown for MSG

Table 2
Target – non-target taste quality scores of the tastants (mean and [SD]).

Concentration	Tastant (quality)				
	Sucrose (Sweet)	Sodium Chloride (NaCl; Salty)	Citric Acid (Sour)	Monosodium Glutamate (MSG; Meaty)	Quinine Hydrochloride (Bitter)
Low	49.0 (27.2) ***	41.7 (31.8) ***	26.9 (28.9) ***	21.3 (31.9) ***	47.4 (31.4) ***
High	72.7 (24.7) ***	69.2 (22.9) ***	54.3 (27.8) ***	27.6 (38.5) ***	70.1 (30.7) ***

*** $p < .0001$, using one-sample Wilcoxon test with mu = 0.

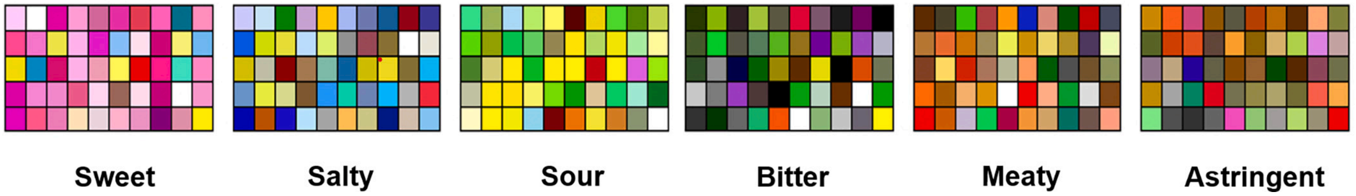

Fig. 2. Color Matches for all high-concentrated solutions. Each block represents a separate solution (i.e., from left to right, Sweet, Salty, Sour, Bitter, Meaty, Astringent). Each cell is a participant's color choice.

(meaty), and orange/brown for tannic (astringent). For quinine (bitter) solutions, green was the most common color chosen for the low concentration solution, whilst an even number of participants chose green and black/white/grey for the high concentration (grey accounted for 10 matches, black for 5, white for 2; see Table 3). Post-hoc chi-squared tests – conducted only on significant color-solution mappings – confirmed that the modal-color (or colors, as for bitter solutions) was responsible for the non-random distribution of the mapping observed in the sample.

5.2.2. Texture-solution Chi Square tests

As shown in Table 4, participants tended to select very smooth textures (1500 grit) for sweet tastes, moderately smooth/rough textures (180 grit) for salty tastes, moderately smooth/rough (180 grit) to rough textures (80 grit) for sour, moderately smooth/rough (180 grit) to very rough textures (40 grit) for bitter tastes, smooth (800 grit) to moderately smooth/rough (180 grit) for umami, and a rough texture (80 grit) for high-astringent taste solutions (with no consistent pairings for low-astringency). For each solution – barring high citric acid - the modal texture was responsible for the non-random distribution of the significant texture-solution mappings observed in the sample.

5.2.3. Shape-solution Chi Square tests

For all solutions there were significant chi-squares pertaining to the shape mappings (i.e., with alpha adjusted by solution; 0.05/6). As summarized in Table 5, participants tended to select smooth and symmetric shapes for sucrose tastes, moderately complex shapes for salty tastes (with low salty being smooth, and high complex), angular and asymmetric shapes for sour tastes (with more complex shapes for high vs. low concentration), and very complex and asymmetric shapes for bitter tastes (with low bitter, smooth; and high bitter more angular). For meaty tastes, asymmetric but smooth shapes were chosen (increasing in complexity with concentration), and for astringent solutions, smooth shapes were chosen – but for low, this was symmetric and simple – and for high, it was complex and asymmetric. The modal chi squares indicate that for all solutions (barring high MSG), the modal shape was responsible for the solution-texture mappings.

5.3. Mechanisms: Valence, intensity and real world associations

5.3.1. Mediation by valence

There were moderate to strong positive standardized correlations (r') between color-, texture-, shape-liking and solution-liking. One-sample *t*-tests (comparing the standardized correlation to a mu of zero [i.e., no correlation]) – were all significant (see Table 6 below). Thus, participants tended to match solutions they liked, to colors, textures and shapes that they liked.

5.3.2. Mediation by intensity

RM-ANOVAs (with the factors solution-type and concentration) were run on color-saturation values, and perceived-roughness (of sandpapers selected) separately. All results are shown in Table 7 and in Figs. 4 and 5.

There was a main effect of solution concentration on color saturation, and perceived roughness – indicating more saturated colors and rougher sandpapers were selected for high (relative to low) concentrated solutions (see Table 7). Solution Type also had a significant main effect on color saturation, and this suggests that some solutions were matched

Table 3
Color mappings for each solution at high and low concentrations and modal color choice (in bold).

		Color solution mappings ($N = 50$)							Chi square tests of independence	
		Orange/Brown	Yellow	Green	Blue	Purple	Pink/Red	Grey/Black/White	Overall $\chi^2(6)$	Post-Hoc χ^2 (1)
Sweet	Low	2	3	6	7	4	**27**	1	68.19***	64.44***
	High	2	5	2	3	2	**34**	2	118.89***	117.88***
Salty	Low	11	8	8	**16**	0	3	4	24.21***	12.82**
	High	7	3	10	**20**	1	4	5	34.01***	27.02***
Sour	Low	8	9	**17**	8	1	6	1	25.05***	15.88**
	High	6	15	**22**	3	0	3	1	56.98***	36.08***
Bitter	Low	5	3	**17**	3	2	5	15	32.05***	15.88**
	High	5	3	**17**	1	6	1	**17**	41.02***	15.88**
Meaty	Low	**14**	5	10	6	1	7	7	13.95^{+}	–
	High	**22**	3	9	2	2	9	3	41.12***	36.08***
Astringent	Low	**13**	5	10	5	2	3	12	16.65^{+}	–
	High	**20**	2	14	1	2	6	5	43.26***	27.02***

*** $p < .001$, ** $p = .011$ (alpha adjusted family wise; 0.05/7 colors), $^{+}$ $p < .05$.

Table 4
Texture-Solution Mappings Contingency Table.

Solution		Texture and solution mappings ($N = 50$)					Chi Square tests of independence	
		Very smooth (1500 grit)	Smooth (800 grit)	Moderately smooth/rough (180 grit)	Rough (80 grit)	Very rough (40 grit)	χ^2 (4)	χ^2 (1)
Sweet	Low	**26**	17	5	2	0	49.40**	32.00**
	High	**22**	19	6	1	2	38.60**	18.00**
Salty	Low	5	14	**24**	5	2	32.60**	24.5**
	High	2	8	**18**	13	8	16.09*	8.58*
Sour	Low	3	9	**21**	12	5	20.00**	15.13**
	High	2	10	14	**17**	7	13.80*	6.13
Bitter	Low	1	5	**19**	13	12	20.00**	10.13*
	High	2	1	5	16	**26**	46.20**	32.00**
Umami	Low	3	**23**	13	8	3	28.00**	21.13**
	High	6	5	**18**	15	6	14.60*	8.00*
Astringent	Low	12	13	**16**	6	3	11.40	–
	High	1	6	10	**19**	14	19.40**	10.13*

[*] $p < .00833$ (family-wise alpha adjusted for taste-solution quality).
[**] $p < .001$.

Table 5
Shape-solution contingency table.

Solution quality		Shape and Solution mappings ($N = 50$)								Chi Square tests of independence	
		Shape 1	Shape 2	Shape 3	Shape 4	Shape 5	Shape 6	Shape 7	Shape 8	Overall	Modal
										χ^2 (7)	χ^2 (1)
Sweet	Low	10	**16**	3	15	1	5	0	0	48.6**	17.38**
	High	11	**17**	2	8	4	7	0	1	85.6**	21.13**
Salty	Low	3	6	8	**15**	3	6	1	8	58.1**	14.00**
	High	6	3	**9**	3	**9**	4	8	8	28.6**	22.90**
Sour	Low	4	1	**14**	5	6	4	10	6	25.8**	10.98**
	High	5	0	9	2	9	6	**13**	8	37.8**	8.33*
Bitter	Low	1	2	9	2	7	3	11	**15**	48.6**	14.00**
	High	2	0	3	2	9	1	**19**	14	84.0**	29.73**
Umami	Low	1	14	2	**16**	2	4	3	8	93.0**	17.38**
	High	1	5	4	10	3	7	8	**12**	53.3**	6.05
Astringent	Low	2	**18**	5	8	0	5	3	9	50.4**	25.25**
	High	5	1	7	5	2	4	10	**16**	61.3**	17.38**

[*] $p < .00833$ (family-wise alpha adjusted for solution quality).
[**] $p < .005$.

Table 6
Standardized Correlations for the Valence Mediation.

Type of correlation	Standardized correlation value r′ (SD)	One sample *t*-test (mu = 0) t (49)
Color- and solution-liking	0.46 (0.46)	7.08**
Texture- and solution-liking	0.70 (0.52)	9.28**
Shape- and solution-liking	0.53 (0.30)	12.06**

[**] *$p < 0.001$.*

to more saturated color selections than others (see Figs. 4 and 5).

While there was a main effect of Solution Type on perceived roughness, this main effect was qualified by a significant interaction between Concentration and Solution Type. As shown Fig. 3, while high (vs. low) concentrated solutions were associated with rougher textures, the magnitude of this difference depended on the type of solution. There was no significant interaction for the RM-ANOVA run on color saturation values (see Table 7).

5.3.3. Participants' rationale for their CMC choices

The proportion of participants who based their mappings of real-

Table 7
RM-ANOVAs for the Intensity Account (Mediation of CMCs by Intensity).

RM-ANOVA type	Effect	Degrees of freedom		RM-ANOVA results		η_p^2
		df (Effect)	df (Error)	F	p	
Color saturation	Concentration	1	49	24.79	<0.001	0.34
	Solution	4.03	197.45	7.35	<0.001	0.13
	Interaction	3.86	189.37	1.50	0.205	0.03
Perceived roughness	Concentration	1	49	50.04	<0.001	0.51
	Solution	5	245	32.44	<0.001	0.40
	Interaction	5	245	6.07	<0.001	0.11

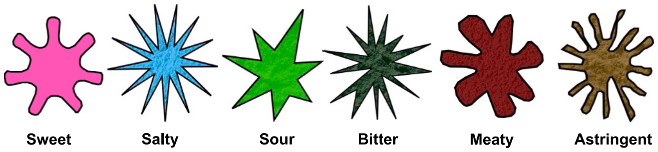

Fig. 3. Prototypical color, texture and shape matches for all high-concentrated solutions. Each object represents a separate solution (i.e., from left to right, Sweet, Salty, Sour, Bitter, Meaty, Astringent).

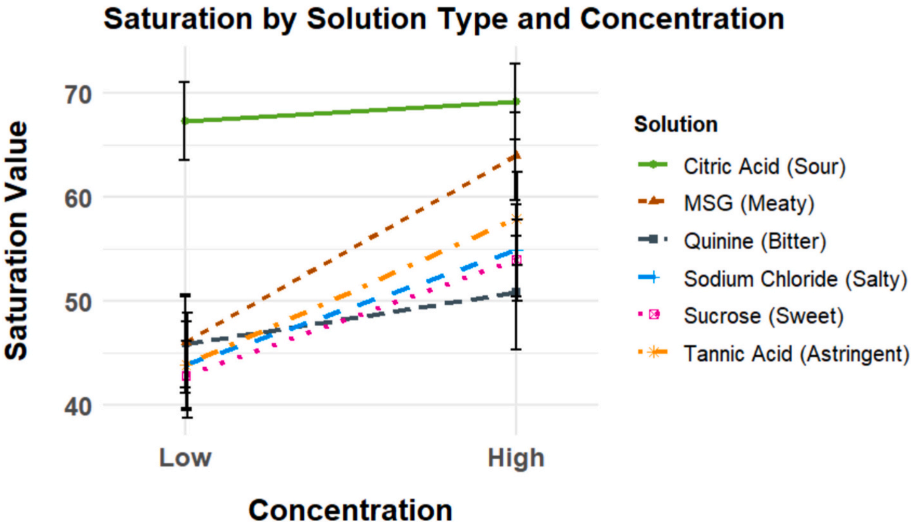

Fig. 4. Solution intensity (concentration) on color saturation.

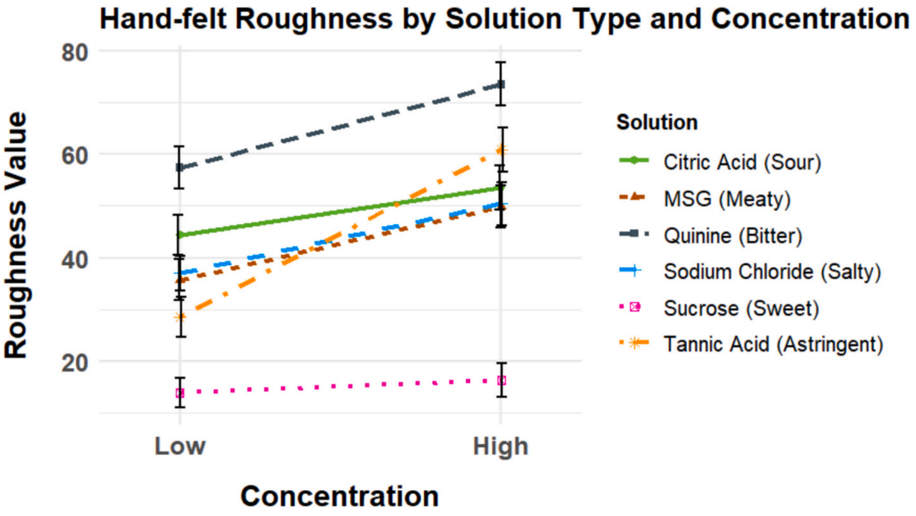

Fig. 5. Solution intensity (concentration) on perceived sandpaper roughness.

world associations, intensity-matching, and liking and exemplars of these rationales for each CMC are detailed in Table 8. People's color matches to solutions could be explained primarily in terms of the real world associations – followed by liking (valence based) and intensity matching. Conversely, textures and shapes were matched to solutions, primarily based on intensity and liking, and to a lesser extent by real world associations. Very few matches were classified as other, and these tended to reflect unsure matches or matches perceived as automatic/innate.

Table 8
Participants' rationale for their choice of CMCs.

Mapping	Value	Type of explanation			
		Real world associations	Intensity matching	Valence based	Other
Color solution	N (%)	39 (78 %)	13 (26 %)	20 (40 %)	7 (14 %)
	Example	*"I chose yellow for sour, because lemons are sour"*	*"For the samples with stronger tastes, I chose bright colors"*	*"I picked green colors for tastes that I didn't like, as they reminded me of things that are disgusting, like rubbish"*	*"When I tasted the solution, the color came to mind automatically"*
Texture solution	N (%)	12 (24 %)	37 (64 %)	23 (46 %)	4 (8 %)
	Example	*"Salty – rough as salt crystals"*	*"The more intense the taste, the rougher the texture I chose"*	*"Sweet was more pleasant so was paired with nicer textures."*	*"because some are salty and bittery"*
Shape solution	N (%)	3 (6 %)	32 (64 %)	29 (58 %)	4 (8 %)
	Example	*"Germ shape because I used to take water mixed with Salt because I was sick"*	*"The higher the intensity, the bolder and spikier the shape is"*	*"For the tastes that were more strong and not as enjoyable, I picked the shapes that were sharp around the outside"*	*"The shape was totally a guess for me"*

5.4. Confidence in match

A one way RM-ANOVA with the factor Mapping-type (color-, texture-, shape- solution) was run on confidence in match ratings. There was no significant effect of Mapping-type, $F(2, 98) = 0.86$, $p = .426$, $\eta_p^2 = 0.02$, suggesting that people were comparably confident in terms of their color-solution, texture-solution and shape-solution matches. On average, participants tended to rate their confidence in matches as two-thirds of the scale – i.e., Mean (SD)'s ranging from 66.40 (18.0) for color matches to 68.8 (16.5) for texture matches – suggesting they were generally confident in matches made.

6. Discussion

In the current study, people made reliable – i.e., consistent across the sample – color, texture, and shape mappings to astringent solutions, as well as real-tastants. Namely, people tended to pick orange/brown colors, rough textures, and squiggly (round, asymmetric) shapes for astringent solutions. Mappings made to the basic tastants were generally in line with those reported in previous studies using taste words - i.e., sweet was paired with red/pink, smooth textures, and round symmetric shapes; salty with blue colors, moderately rough textures and angular shapes; sour with green/yellow hues, rough textures, angular shapes; bitter with green/black hues, rough textures, angular shapes; and meaty with orange/brown hues, moderately smooth/rough textures and round asymmetric (squiggly) shapes (Di Stefano & Spence, 2022; Motoki, Marks, & Velasco, 2023; Motoki, Spence, & Velasco, 2023; Spence et al., 2015; Spence & Levitan, 2022; Velasco, Woods, Petit, et al., 2016). The most cited reason for color matches was in terms of real-world associations (e.g., lemons are yellow and sour), followed by valence (liking), and intensity. Conversely, intensity was the most cited reason for texture and solutions mappings (i.e., shape and solution both felt rough/smooth), as well as shape and solution mappings (e.g., the shape looked spiky, and the solution felt spiky in the mouth). While intensity matching was reported to occur, it remains unclear what was driving this matching – i.e., was structural based (similar neural codes) or emotionally or semantically mediated intensity (Motoki, Marks, & Velasco, 2023; Motoki, Spence, & Velasco, 2023). For both texture-solution and shape-solution CMCs, valence was the second most cited reason for mappings, followed by real-world associations. People were moderately and comparably confident in terms of their color, texture, and shape matches to the solutions.

It is interesting to speculate why color-solution matches were primarily driven by real-world associations (related to the statistical account), whilst other matches (i.e., solution- shape, and texture), were dominantly driven by intensity matching. Color associations with taste/oral-somatosensory properties may form from real-world associations, because they co-occur in environmental objects and thus can be learnt readily (Ernst, 2007). One example of this, is the color and taste changes that co-occur during fruit ripening – e.g., unripe fruits tend to be green and sour/bitter, whilst ripe fruits tend to be warmer colored (e.g., red/pink/golden) and sweet (Raevskiy et al., 2022; Spence et al., 2015; Spence & Levitan, 2021). Another example of the co-occurrence of colors and taste/foods can be found in color-grapheme CMCs – i.e., most people will pair the letter 'A' to red (or green) – and when people are asked to provide the first word they can think of, which begins with the letter 'A', most respondents say apples (which are green/red; Simner et al., 2005; Mankin & Simner, 2017). This suggests that outside of taste, other color-based CMCs may also be related to real word associations. By contrast, there may be *less* reliable, learnt associations between solutions- and textures/shapes, making mappings here based primarily on structural similarities.

While not the primary reason reported for color-mappings, in line with the intensity account there was a significant effect of solution intensity on color saturation – and this was comparable across astringent and basic taste solutions. Similarly, there was a strong effect of solution concentration on perceived intensity (roughness) of texture matches – and this seemed particularly so for non-sweet solutions. For shapes, structural similarities between shapes (i.e., how people *expected* them to feel on the tongue) and solutions (i.e., how they felt on the tongue) were reported as the primary reason for mappings. Relatedly, some participants rationales appeared hardwired or at least with little influence of learning (e.g., "*When I tasted the solution, the color came to mind automatically*"), which may support structural mediation for these CMCs. Intensity matching observed here, may also provide support for the structural account, as neural patterns that represent stimulus magnitude are proposed to be coded similarly across visual, tactile and chemosensory modalities (Spence, 2011). While it is possible that structural mediation occurred – it is important to note that more concentrated foods may also be packaged in more rough, saturated, etc. colors – e.g., light blue vs. dark blue for light and full-fat milk respectively (Tijssen et al., 2017). Thus, the effect of solution concentration on mappings reported may partly, at least, be driven by real world associations (statistical account; Saluja & Stevenson, 2018).

Valence explained 22 % (color-solution) to 49 % (texture-solution) of the variation in the reported mappings. This result is consistent with prior research examining chemosensory and non-chemosensory stimulus mappings (e.g., color-taste; Saluja & Stevenson, 2018; shape-taste, Woods et al., 2016; odor-color, Stevenson et al., 2012). Valence appears exclusive – i.e., not related to structural or statistical based mechanisms – and potentially more relevant for flavor-related cross modal mappings, given the role of food/beverage liking or palatability in ingestive behaviors.

While the current study and past studies show that three mechanisms – real world associations (related to the statistical account), valence (related to the semantic account), and intensity matching (related to the structural account) – play pertinent roles in the observed cross-modal mappings, and more generally in flavor CMCs, it remains unclear *when* these accounts drive the cross-modal mappings and if these mechanisms play a similar relative importance to one another across development. For example, it remains unclear if real-world associations also act as the primary mechanism driving color-solution mappings in children – and when intensity and valence tuning of these matches develops (Meng et al., 2023). An understanding of when, during development, flavor cross-modal CMCs develop has pertinent implications to understanding development of flavor-perception and binding, and for improving food-marketing to children (especially of health-based foods). Relatedly, whether these reported mappings can be used to bias expected and actual flavor of astringent foods/drinks remains relatively unknown – although few recent studies showing that astringent substances (wine, coffee) are biased by textural roughness (e.g., rough vs. smooth cup), suggest that they likely can (Carvalho et al., 2020; Wang & Spence, 2018).

In relation to our findings few limitations need to be considered. First, tannic acid was a colored solution (pale brown/red) and matches to tannic acid also seemed to be classified as orange/brown. While we asked people to close their eyes, it is possible that some participants may not have complied with instructions and seen the solutions' color, which in turn *may* have biased their mappings. This seems unlikely for three reasons. First, no participant reported the tannic acid's color as the basis for their color-solution matches. Second, participants were seated opposite the experimenter during the study, reducing the likelihood of non-compliance with instructions. Third, tannic acid matches appeared more greenish-brown (noting green was the second most selected color), rather than a reddish-brown (see Figs. 1 and 2). Nevertheless, future studies should replicate the study using other colorless – albeit less intense – astringent substances (e.g., tartaric acid; Lawless et al., 1994), so to better ascertain the color mappings to a range of astringent substances.

Another limitation was that low tannic acid was perceived as less astringent than the basic tastes (noting that some basic tastants have astringent properties – e.g., citric acid, and quinine; Lawless et al., 1994)

– which may explain why several mappings to low tannic acid did not reach significance (i.e., texture- and color- low tannic acid mappings). In line with this, previous psychophysical experiments – examining a range of astringent substances (e.g., tannic acid, gallic acid, and catechins) found in wines – have shown that, at lower concentrations, astringent substances tend to be perceived as equally or more bitter than astringent, with the perception of astringency increasing significantly more, relative to bitterness, at higher concentrations (Robichaud & Noble, 1990). Nevertheless, while not significant, mappings made to low tannic acid tended to have similar *patterns* to those made to high-astringency solutions (e.g., similar color, texture and shape selections) – suggesting the strength but not pattern of the current findings were shaped by the perceived astringency of tannic acid. Further, our sample size was largely comprised of females (i.e. 86 % females), potentially limiting generalizability to males. As the literature on differences in taste and astringency percept between males and females is mixed (see Schroeder, 2010), it remains unclear if sex differences in these CMCs are expected. Thus, more research is needed to examine if gender differences exist in gustatory- and astringency- visual CMCs. Finally, participants were exposed to the words, sweet, sour, salty, meaty, bitter and astringent during the experiment, when rating the solutions on these properties. This may have introduced semantic associations – e.g., seeing meaty and thinking of brown. Future studies should thus rule out this possibility, by asking participants to make taste-quality ratings at the *end* of the experiment (after CMCs have been made).

In conclusion, akin to the basic tastants, astringent substances – such as tannic acid – have reliable color, shape and texture matches in the general, non-synesthetic population. Astringent solutions, across the sample, were most reliably paired with orange/brown hues, rough textures and asymmetric, round but complex (squiggly) shapes. Mappings to the basic tastants were consistent with past studies. While three mechanisms appeared responsible for all mappings – i.e., real-world associations, valence and similarities in intensity between sensory stimuli – the relative importance of these mechanisms appears to vary, depending on the CMC in question. More research is now needed to understand when – during development - these mechanisms drive flavor crossmodal correspondences, and their effect on expected and perceived flavor of astringent foods/drinks.

CRediT authorship contribution statement

Supreet Saluja: Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Talia Ciscato:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Anjoli Mistry:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Thomas Hummel:** Writing – review & editing, Methodology, Conceptualization. **Charles Spence:** Writing – review & editing, Methodology, Conceptualization. **Richard J. Stevenson:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization.

Ethical statement

Ethics was approved by the Macquarie University Human Research Ethics Committee (520241685255953), dated March 15th, 2024 and valid until March 15th 2029.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodqual.2025.105518.

Data availability

Data will be made available on request.

References

Barbosa Escobar, F., & Wang, Q. J. (2023). Tasty vibes: Uncovering crossmodal correspondences between tactile vibrations and basic tastes. *Food Research International, 174*, Article 113613. https://doi.org/10.1016/j.foodres.2023.113613

Biggs, L., Juravle, G., & Spence, C. (2016). Haptic exploration of plateware alters the perceived texture and taste of food. *Food Quality and Preference, 50*, 129–134. https://doi.org/10.1016/j.foodqual.2016.02.007

Carvalho, F. M., Moksunova, V., & Spence, C. (2020). Cup texture influences taste and tactile judgments in the evaluation of specialty coffee. *Food Quality and Preference, 81*, Article 103841. https://doi.org/10.1016/j.foodqual.2019.103841

Cytowic, R. E. (2003). *The man who tasted shapes*. MIT Press.

Di Stefano, N., & Spence, C. (2022). Roughness perception: A multisensory/crossmodal perspective. *Attention, Perception, & Psychophysics, 84*(7), 2087–2114. https://doi.org/10.3758/s13414-022-02550-y

Di Stefano, N., & Spence, C. (2023). Perceptual similarity: Insights from crossmodal correspondences. *Review of Philosophy and Psychology*. https://doi.org/10.1007/s13164-023-00692-y

Ekman, P., & Friesen, W. V. (1976). *Pictures of facial affect*. Consulting Psychologists Press.

Ernst, M. O. (2007). Learning to integrate arbitrary signals from vision and touch. *Journal of Vision, 7*(5/7), 1–14. https://doi.org/10.1167/7.5.7

Escobar, F. B., Wang, Q. J., Corredor, A., & Velasco, C. (2022). The taste of visual textures. *Food Quality and Preference, 100*, 104602. https://doi.org/10.1016/j.foodqual.2022.104602

Fleming, E. E. (2015). *Psychophysical, physiological, and semantic characterization of oral astringents*. Master's dissertation. PS libraries. The Pennsylvania State University https://etda.libraries.psu.edu/files/final_submissions/10686.

Gawel, R., Oberholster, A., & Francis, I. L. (2000). A 'mouth-feel wheel': Terminology for communicating the mouth-feel characteristics of red wine. *Australian Journal of Grape and Wine Research, 6*(3), 203–207. https://doi.org/10.1111/j.1755-0238.2000.tb00180.x

Green, B. G. (1993). Oral astringency: A tactile component of flavor. *Acta Psychologica, 84*(1), 119–125. https://doi.org/10.1016/0001-6918(93)90078-6

Ho, H.-N., Van Doorn, G. H., Kawabe, T., Watanabe, J., & Spence, C. (2014). Colour-temperature correspondences: When reactions to thermal stimuli are influenced by colour. *PLoS ONE, 9*(3), Article e91854. https://doi.org/10.1371/journal.pone.0091854

Howell, D. C. (2010). *Statistical methods for psychology* (7th ed.). Belmont: Wadsworth Cengage Learning.

Ikeda, K. (2002). New seasonings. *Chemical Senses, 27*(9), 847–849. (Reprinted from 1909 https://doi.org/10.1093/chemse/27.9.847).

Koch, C., & Koch, E. (2003). Preconceptions of taste based on color. *The Journal of Psychology, 137*(3), 233–242. https://doi.org/10.1080/00223980309600611

Lawless, H. T., Corrigan, C. J., & Lee, C. B. (1994). Interactions of astringent substances. *Chemical Senses, 19*(2), 141–154. https://doi.org/10.1093/chemse/19.2.141

Lee, B. P., & Spence, C. (2022). Crossmodal correspondences between basic tastes and visual design features: A narrative historical review. *I-Perception, 13*(5), 1–27. https://doi.org/10.1177/20416695221127325

Mankin, J. L., & Simner, J. (2017). A is for apple: The role of letter-word associations in the development of grapheme-colour synaesthesia. *Multisensory Research, 30*(3–5), 409–446. https://doi.org/10.1163/22134808-00002554

Marks, L. E. (1975). On colored-hearing synesthesia: Cross-modal translations of sensory dimensions. *Psychological Bulletin, 82*(3), 303–331. https://doi.org/10.1037/0033-2909.82.3.303

Meng, X., Chen, N., Ishida, J., Watanabe, K., & Murakami, T. (2023). Crossmodal correspondences between visual features and tastes in preschoolers: An exploratory study. *Frontiers in Psychology, 14*, Article 1226661. https://doi.org/10.3389/fpsyg.2023.1226661

Motoki, K., Marks, L. E., & Velasco, C. (2023). Reflections on cross-modal correspondences: Current understanding and issues for future research. *Multisensory Research, 37*(1), 1–23. https://doi.org/10.1163/22134808-bja10114

Motoki, K., Spence, C., & Velasco, C. (2023). When visual cues influence taste/flavour perception: A systematic review. *Food Quality and Preference, 111*, Article 104996. https://doi.org/10.1016/j.foodqual.2023.104996

O'Mahony, M. (1983). Gustatory responses to nongustatory stimuli. *Perception, 12*(5), 627–633. https://doi.org/10.1068/p120627

O'Mahony, M., Goldenberg, M., Stedmon, J., & Alford, J. (1979). Confusion in the use of the taste adjectives 'sour' and 'bitter'. *Chemical Senses, 4*(4), 301–318. https://doi.org/10.1093/chemse/4.4.30

Osgood, C. E., Suci, G. J., & Tannenbaum, P. H. (1957). *The measurement of meaning*. University of Illinois Press.

Palmer, S., & Schloss, K. (2010). An ecological valence theory of human color preference. *Proceedings of the National Academy of Sciences, 107*(19), 8877–8882. https://doi.org/10.1073/pnas.0906172107

Palmer, S., Schloss, K., & Whiteford, K. (2013). Music-color associations to classical music in synesthetes and non-synesthetes: The surprising role of emotion. *Journal of Vision, 13*(9), 1323. https://doi.org/10.1167/13.9.1323

Piqueras-Fiszman, B., & Spence, C. (2012). The influence of the feel of product packaging on the perception of the oral-somatosensory texture of food. *Food Quality and Preference, 26*(1), 67–73. https://doi.org/10.1016/j.foodqual.2012.04.002

Pistolas, E., & Wagemans, J. (2023). Crossmodal correspondences and interactions between texture and taste perception. *i-Perception, 14*(2), Article 20416695231163473. https://doi.org/10.1177/20416695231163473

Raevskiy, A., Bubnov, I., Chen, Y. C., & Sakai, N. (2022). Differences in color representations of tastes: Cross-cultural study among Japanese, Russian and Taiwanese. In *International conference on human-computer interaction* (pp. 378–395). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-031-06038-0_28.

Riofrio-Grijalva, R., Lago, M., Fabregat-Amich, P., Guerrero, J., Cuesta, A., & Vázquez-Araújo, L. (2020). Relationship between tactile stimuli and basic tastes: CATA with consumers with visual disability. *Journal of Sensory Studies, 35*(1), Article e12549. https://doi.org/10.1111/joss.12549

Robichaud, J. L., & Noble, A. C. (1990). Astringency and bitterness of selected phenolics in wine. *Journal of the Science of Food and Agriculture, 53*(3), 343–353. https://doi.org/10.1002/jsfa.2740530307

Saluja, S., & Stevenson, R. J. (2018). Cross-modal associations between real tastes and colors. *Chemical Senses, 43*(7), 475–480. https://doi.org/10.1093/chemse/bjy033

Schroeder, J. A. (2010). Sex and gender in sensation and perception. In J. Chrisler, & D. McCreary (Eds.), *Handbook of gender research in psychology*. New York, NY: Springer. https://doi.org/10.1007/978-1-4419-1465-1_12.

Shermer, D. Z., & Levitan, C. A. (2014). Red hot: The crossmodal effect of color intensity on perceived piquancy. *Multisensory Research, 27*(3–4), 207–223. https://doi.org/10.1163/22134808-00002457

Simner, J., Ward, J., Lanz, M., Jansari, A., Noonan, K., Glover, L., & Oakley, D. A. (2005). Non-random associations of graphemes to colours in synaesthetic and non-synaesthetic populations. *Cognitive Neuropsychology, 22*(8), 1069–1085. https://doi.org/10.1080/02643290500200122

Spence, C. (2011). Crossmodal correspondences: A tutorial review. *Attention, Perception & Psychophysics, 73*(4), 971–995. https://doi.org/10.3758/s13414-010-0073-7

Spence, C. (2019). Crossmodal contributions to the perception of piquancy/spiciness. *Journal of Sensory Studies, 34*(1), Article e12476. https://doi.org/10.1111/joss.12476

Spence, C. (2023). Explaining visual shape-taste crossmodal correspondences. *Multisensory Research, 36*, 313–345. https://doi.org/10.1163/22134808-bja10096

Spence, C., & Levitan, C. A. (2021). Explaining Crossmodal Correspondences Between Colours and Tastes. *i-Perception, 12*(3), Article 20416695211018223. https://doi.org/10.1177/20416695211018223

Spence, C., & Levitan, C. A. (2022). Exploring the links between colours and tastes/flavours. *Journal of Perceptual Imaging, 5*. https://doi.org/10.2352/J.Percept.Imaging.2022.5.000408, 000408-1-000408-000416.

Spence, C., & Ngo, M. (2012). Assessing the shape symbolism of the taste, flavour, and texture of foods and beverages. *Flavour, 1*, 12. https://ora.ox.ac.uk/objects/uuid:75f14053-3f56-4b10-9f53-a8ec0c8f4221.

Spence, C., Wan, X., Woods, A., Velasco, C., Deng, J., Youssef, J., & Deroy, O. (2015). On tasty colours and colourful tastes? Assessing, explaining, and utilizing crossmodal correspondences between colours and basic tastes. *Flavour, 4*(1), 23. https://doi.org/10.1186/s13411-015-0033-1

Stevens, S. S. (1957). On the psychophysical law. *Psychological Review, 64*(3), 153–181. https://doi.org/10.1037/h0046162

Stevenson, R. J. (2009). *The psychology of flavour*. Oxford University Press. https://global.oup.com/academic/product/the-psychology-of-flavour-9780199539352?cc=us&lang=en&.

Stevenson, R. J., Rich, A., & Russell, A. (2012). The nature and origin of cross-modal associations to odours. *Perception, 41*(5), 606–619. https://doi.org/10.1068/p7223

Tijssen, I., Zandstra, E. H., de Graaf, C., & Jager, G. (2017). Why a 'light' product package should not be light blue: Effects of package colour on perceived healthiness and attractiveness of sugar- and fat-reduced products. *Food Quality and Preference, 59*, 46–58. https://doi.org/10.1016/j.foodqual.2017.01.019

Tomasik-Krótki, J., & Strojny, J. (2008). Scaling of sensory impressions. *Journal of Sensory Studies, 23*(2), 251–266. https://doi.org/10.1111/j.1745-459X.2008.00153.x

Velasco, C., Woods, A., Liu, J., & Spence, C. (2016). Assessing the role of taste intensity and hedonics in taste-shape correspondences. *Multisensory Research, 29*(1–3), 209–221. https://doi.org/10.1163/22134808-00002489

Velasco, C., Woods, A. T., Petit, O., Cheok, A. D., & Spence, C. (2016). Crossmodal correspondences between taste and shape, and their implications for product packaging: A review. *Food Quality and Preference, 52*, 17–26. https://doi.org/10.1016/j.foodqual.2016.03.005

Vidal, L., Giménez, A., Medina, K., Boido, E., & Ares, G. (2015). How do consumers describe wine astringency? *Food Research International, 78*, 321–326. https://doi.org/10.1016/j.foodres.2015.09.025

Wang, Q. J., & Spence, C. (2018). A smooth wine? Haptic influences on wine evaluation. *International Journal of Gastronomy and Food Science, 14*, 9–13. https://doi.org/10.1016/j.ijgfs.2018.08.002

Wang, Q. J., Wang, S., & Spence, C. (2016). Turn Up the Taste": Assessing the Role of Taste Intensity and Emotion in Mediating Crossmodal Correspondences between Basic Tastes and Pitch. *Chemical senses, 41*(4), 345–356. https://doi.org/10.1093/chemse/bjw007

Woods, A. T., Marmolejo-Ramos, F., Velasco, C., & Spence, C. (2016). Using single colors and color pairs to communicate basic tastes II: Foreground-background color combinations. *i-Perception, 7*(5), Article 2041669516663750. https://doi.org/10.1177/2041669516663750

Woods, A. T., & Spence, C. (2016). Using single colors and color pairs to communicate basic tastes. *i-Perception, 7*(4), Article 2041669516658817. https://doi.org/10.1177/2041669516658817

Zhu, Y., Thaploo, D., Han, P., & Hummel, T. (2023). Processing of sweet, astringent and pungent oral stimuli in the human brain. *Neuroscience, 520*, 144–155. https://doi.org/10.1016/j.neuroscience.2023.03.011