Food Quality and Preference 112 (2023) 105009

Contents lists available at ScienceDirect

Food Quality and Preference

journal homepage: www.elsevier.com/locate/foodqual

The taste of colours

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ARTICLE INFO

Keywords:
Colour
Taste
Crossmodal correspondences
Statistical regularities
Semantic congruence

ABSTRACT

A multitude of crossmodal correspondences have now been documented between taste (gustation) and visual features (such as hue). In the present study, new analytical methods are used to investigate taste-colour correspondences in a more fine-grained manner while also investigating potential underlying mechanisms. In Experiment 1, image processing analysis is used to evaluate whether searching online for visual images associated with specific taste words (e.g., bitter, sweet) generates outcomes with colour proportions similar to those that have been documented in the literature on taste–colour correspondences. Colour–taste matching tasks incorporating a much wider colour space than tested in previous studies, were assessed in Experiments 2 and 3. Experiments 3 and 4 assessed the extent to which the statistical regularities of the environment, as captured by food object categories, might help to explain the aforementioned correspondences and to what extent the correspondences are present in online content associated with specific tastes, respectively. Experiment 5 evaluated the role of statistical regularities in underpinning colour-taste correspondences related to the stage of ripening of fruit. Overall, the findings revealed consistent associations between specific colours and tastes, in a more nuanced manner than demonstrated in previous studies, while at the same time also showing that both food object categories and the stage of fruit ripening significantly influenced colour and taste perceptions. This, in turn, suggests that people might base these correspondences on both the foods present in their environments, as well as the natural changes that they undergo as they ripen. The results are discussed in light of the different accounts that have been suggested to explain colour-taste correspondences.

1. Introduction

Vision is critical when it comes to setting our food and drink expectations and thereafter our flavour perception (e.g., Delwiche, 2012; Hurling & Shepherd, 2003; Piqueras-Fiszman & Spence, 2015; Sun and Gauthier, in press). Indeed, it has been suggested that vision and retronasal olfaction may provide some of the most important cues as far as setting people's expectations associated with the likely taste of foods and beverages (Hutchings, 1977; Stevenson, 2009). Perhaps unsurprisingly, the research that has been published to date has documented a number of associations between visual features and tastes (see Spence, 2023, for a review). Some of these associations fall within the literature on crossmodal correspondences, that is, the sometimes surprising, associations that have repeatedly been documented between features present in (or assessed via) different senses (Spence, 2011, 2022; Walker, 2016).

A variety of crossmodal correspondences between visually-presented features including shape curvature and symmetry (Turoman et al., 2018), textures (Barbosa Escobar et al., 2022), and colours (Saluja & Stevenson, 2018), on the one hand, and taste and/or taste words on the other, have been documented to date. For instance, people typically tend to associate sweetness with roundness and pinkish-red hues and other tastes such as bitterness and sourness with shape angularity and yellow/green hues (e.g., Velasco et al., 2015, 2016).

In the present study, we focus on taste–colour associations. As such, it is important to clarify first what taste and colour are. Taste refers to the basic gustatory sensations experienced in the oral cavity, especially the tongue, with the basic qualities of taste commonly assumed to refer to sweet, sour, salty, bitter, and increasingly also umami (e.g., Avery et al., 2020). People often confuse taste with flavour. Technically speaking, though, flavour relates to the interaction between taste,

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https://doi.org/10.1016/j.foodqual.2023.105009
Received 31 July 2023; Received in revised form 3 October 2023; Accepted 3 October 2023
Available online 11 October 2023
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olfaction, and possibly also trigeminal sensations that form a unitary percept (Auvray & Spence, 2008; Spence, Smith, & Auvray, 2015). In fact, all of the senses contribute to the perception of flavour, either in terms of helping to set people's flavour predictions, and/or in terms of contributing directly to flavour perception (Spence, 2017; Stevenson, 2009, 2014). Colour perception is intricately linked to the human visual system's sensitivity to electromagnetic radiation within the visible spectrum. This sensitivity is contingent upon the specific wavelength of light, which, in turn, determines the appearance of objects and light sources through three fundamental perceptual dimensions: hue, saturation, and lightness. Hue corresponds to the pure spectrum of colours, often equated with colour names such as red, green, and blue. Saturation relates to the perceived degree of whiteness in a colour, while lightness pertains to the intensity of light seemingly reflected from the object. These perceptual dimensions collectively contribute to the comprehensive understanding of colour and its visual representation (Taveras-Cruz et al., 2022).

Over recent decades, a number of studies have explored the associations between tastes and colour hue (e.g., Koch & Koch, 2003; Marks, 1978; O'Mahony, 1983; Spence et al., 2015). Broadly-speaking, the different studies reveal a general tendency for people to associate sweetness with red and pink, sour with green-yellow, salt with blue and white, and bitter with darker colours such as black and brown (e.g., Tomasik-Krotki & Strojny, 2008; Velasco et al., 2016; Wan et al., 2014; see also Spence & Levitan, 2021, for a review).

Whilst the research documents the existence of a number of such crossmodal correspondences between tastes and colour hues and a range of potential explanations have been suggested, there are two major limitations that the present research is designed to address. First, many of the studies involve situations in which the participants were forced to choose from a small set of colour options. Second, it is still not fully clear why it is that people associate seemingly-unrelated visual and gustatory features in the consensual ways that the research shows that they do. The research outlined here involves new analytical approaches (e.g., image processing analysis of colour in relation to taste searches), a more comprehensive colour space in the matching tasks, as well as a new experiment designed to assess how source object changes relate to both colours and tastes. Comparable analytical methods have been used in previous research both in terms of image processing analysis (Motoki, Takahashi, & Spence, 2021) and fine-grained colour scales (Huang et al., 2019, 2020). Notably, though, when it comes to image processing analysis, in contrast to previous research that analysed all the pixels in an image, our study concentrated exclusively on the hue, saturation, and value of the *most salient pixels*, thus ignoring interference from colours in other parts of the background of the image. We also used features extracted with deep learning models to compare the semantic content of images of specific objects and those associated with tastes. In addition, whilst we use a 1536 × 384 px rectangle with HSV values (16384 colour points), some of the previous studies have focused on the default Microsoft Office 127-colour palette. Lastly, previous research using a broader set of colour alternatives, has focused on foods and their flavours (e.g., tea, coffee), with taste ratings associated with them just being one aspect of the studies, whilst the present research focuses exclusively on taste.

Spence and Levitan (2021) recently outlined several potential mechanisms that might lie behind the aforementioned correspondences. They describe four possibilities: the first suggests that colour-taste correspondences may be based on the crossmodal similarity of the component unisensory stimuli (though see Di Stefano & Spence, 2023; Spence & Di Stefano, 2022). The second mechanism indicates that people might be sensitive to the statistical regularities of the environment and, through a process of associative learning, come to internalize those mappings that occur between tastes and colours in our environments (e.g., Maga, 1974; cf. Parise, Knorre, & Ernst, 2014). Spence and Levitan clarify, though, that this mechanism leads to the question of whether colour–taste correspondences may be mediated by a specific source object. In other words, do people sometimes choose to associate colours and tastes because, when asked about these mappings, they use a benchmark object as a reference point (i.e., such as associating yellow and green with sour because they bring to mind citrus fruits, such as lemons and limes, at least if one happens to live in Europe)? Providing some insights into this matter, Speed and her colleagues (2023) recently conducted a study designed to assess whether odour-colour associations were mediated by concurrent verbalization. Their studies revealed that, even though colour associations are somehow related to semantic factors (e.g., odour naming accuracy), they are not based on odour labels.

Finally, Spence and Levitan (2021) point to a potential emotional mediation account of at least some taste-colour correspondences. It is worth noting that this kind of explanation has also been used to explain many other correspondences, such as those between taste and shape or scent and colour (i.e., where a statistical or source object account has yet to be forthcoming; Schifferstein & Tanudjaja, 2004; see Spence, 2020, for a review). The idea here is that the participants in experimental studies might choose to associate tastes and colours on the basis of the affective tone of the individual sensory stimuli. It is important to bear in mind here that the different mechanisms of crossmodal correspondences need not be mutually exclusive but might be complementary when it comes to explaining them (Spence, 2011).

In the present research, the focus is on trying to provide insights into the specific colour spectrum associated with each taste and the explanatory power of the statistical account of taste–colour correspondences. Thereafter, the aim was to assess the extent to which people use source objects, and the transformations that they undergo, to help guide the colour–taste associations. To that end, five studies were conducted that were designed to replicate and extend previous findings on colour–taste correspondences.

In Experiment 1, image processing analysis was used to evaluate whether visual images coming from an online search using specific taste words as search terms leads to image outcomes with most salient areas or objects containing hues that resemble the taste-colour correspondences that have been documented. In Experiment 2, a colour–taste matching task was conducted with a wider colour space, relative to previous studies in order to replicate the findings of Experiment 1. In Experiment 3, Experiment 2 was replicated and extended by adding a question to inquire what came to mind when the participants were performing the matching task in order to assess whether specific source objects guided the associations. In Experiment 4, the aim was to capitalize on the results of Experiment 3 and conduct a new search using the methods developed in Experiment 1. The objective was to evaluate the similarity between images associated with tastes and specific food categories and determine whether the associations documented in Experiment 3 could also be found in images obtained from a web search engine. Finally, in Experiment 5, people's colour and taste associations with fruits at different stages of the ripening process were evaluated. This relates to what are presumed to be correlated changes in both colour and taste, as well as aroma, flavour, and possibly also texture.

2. Experiment 1: Image processing

2.1. Method, procedure, and analyses

This experiment was designed to determine the distribution of colours in the most salient areas of images associated with specific taste words and retrieved online through a search engine. To that end, the retrieved images were processed by extracting the HSV (Hue, Saturation, Value) representations of the pixels' colours in each image's most salient areas as described below.

Image acquisition: Images associated with specific tastes were retrieved using the Google Cloud Platform and the custom search API. The API is used, as opposed to a manual search, because of easiness in downloading the material, and the possibility of specifying the location and language of the results, regardless of where the search was performed. The geolocation was set to the United States of America (US), and the search language to English. The search terms used were: bitter, salty, sour, sweet, and umami, followed by the word food. The API returns the URL to the most relevant images associated with a given search term, as determined by the engine. The first 50 results from the image search were downloaded for further processing to determine the colour distributions in the salient areas. The results used were capped at 50 since additional results would include repeated or unrelated images as they become less relevant or associations are less direct.

Saliency estimation: Images can contain different areas in the foreground and background; however, we were interested in those parts of the image containing the most relevant components, or objects. As such, only some elements in each image are likely suitable for determining the distribution of colours that are associated with a specific taste. The Deep Learning model presented in Kroner et al. (2020) was used to estimate the most salient areas of an image and then consider only those pixels. The model was trained on the SALICON dataset (Jiang et al., 2015). This model takes a raw image as its input and generates a mask indicating a saliency per pixel (See Appendix A for examples of downloaded images and their estimated saliency maps). The saliency was normalised between 0 and 1, and only those pixels with a saliency greater than 0.9 were considered further. Some of the images contained faces or packaging; however, in the images containing faces, the saliency maps highlighted the food and not only the faces. Furthermore, these images represented less than 4% of all the images. Similarly, there were images presenting packaging, but these were less than 2% and, in most cases, the colours featured were in line with the associated food. So, the effect of face and packaging pixels was assumed to be minor, and images were kept as they still represent associations with the visual representation of tastes online.

Colour distributions: All the pixels in the most salient areas were considered per picture. A colour distribution per image was calculated, and then all distributions per image were averaged to form a distribution per taste. Distributions were generated as two-dimensional histograms for hues and values, in a format that allowed for comparison with the results of Experiments 2 and 3. An average distribution over all images was calculated per taste by adding all the individual image distributions and forming a normalised histogram.

Palette: The results of Experiments 1, 2, and 3 are superimposed on the colour palette used for Experiments 2 and 3. The colour palette consisted of a 1536 × 384 px rectangle varying in HSV (see Fig. 1). In this palette's horizontal axis, all hues values in HSV ranging from 0 to 255 are arranged. In the vertical axis, saturation and value vary simultaneously. Value decreases linearly from 255 on the top of the palette to 35 on the bottom. Saturation increases linearly in the first third of the axis from 35 to 254 and is maintained at 254 afterwards. That allows for a wide range of value combinations and saturation levels for each hue. Moreover, the top part of the palette contains lighter colours, with darker ones on the bottom, while always maintaining a hue (as the saturation never drops to 0). This colour palette alternative allows us to quantify variations in hue and brightness. In addition, given that we are using coordinates to represent colour variation, they can be used to estimate a give spatial location (mean) with some measure of variability (standard deviation), in our case the average colour region and its width.

2.2. Results and discussion

The results of this Experiment 1 are visualised in Fig. 2 (Experiment 1). They show that estimates of salient areas of those images that are associated with sweetness have predominantly red hues, notably darker shades. That is mainly due to images depicting desserts, pastries, and chocolates. There is a high concentration of yellow and orange hues and darker shades in those images that were associated with the word 'salty'. There are some elements of blue and lighter reds. These results emerge from images depicting snacks as examples of salty food and using blue elements in the image compositions.

For sour, salient areas mainly depict dark oranges, yellows, and reds. Closer inspection to the images reveals that these colours appear to come from citrus fruits such as lemons, oranges, and grapefruits. Some images also show cocktails, sour candy. In the images associated with bitterness, the range of hues is broader and includes green, yellow, orange, and red. Green is associated with bitter vegetables and fruits, while red comes from some fruits and drinks. Lastly, umami images depict brighter reds and dark browns, which may be linked to the presence of this taste in tomatoes, meats and fermented foods (cf. Ikeda, 2002).

Overall, these results appear to indicate that, although certain image colours match the searched tastes following the documented taste–-colour correspondences (e.g., sweet and red), others did not (e.g., bitterness and green, yellow, orange and red) (Saluja & Stevenson, 2018). Notably, however, previous studies typically include only a selected number of colours. For this reason, in Experiment 2, we move on to evaluate how taste–colour correspondences occur in tasks that include a larger colour spectrum to choose from than previous studies.

3. Experiment 2: Matching task

3.1. Participants

A total of 245 native English speakers from the US took part in the study. Nevertheless, the data from one participant with duplicate answers were removed from the analyses. The final sample consisted of 244 participants (121 males, 119 females, 4 other) aged 18–50 years ($M = 31.99$ years, $SD = 7.84$). The participants were recruited from Prolific (https://www.prolific.com/) and were compensated with GBP 0.45. All of the experiments involving human participants reported here complied with the World Medical Association's Declaration of Helsinki. Before starting each experiment, all of the participants provided their informed consent to take part.

3.2. Apparatus and materials

Unlike previous studies, which have typically used a narrow set of colours to evaluate people's colour-taste associations, we used a colour palette to obtain highly granular data. The colour palette consisted of a 1536 × 384 px rectangle with HSV values as described in Experiment 1 (see Fig. 1).

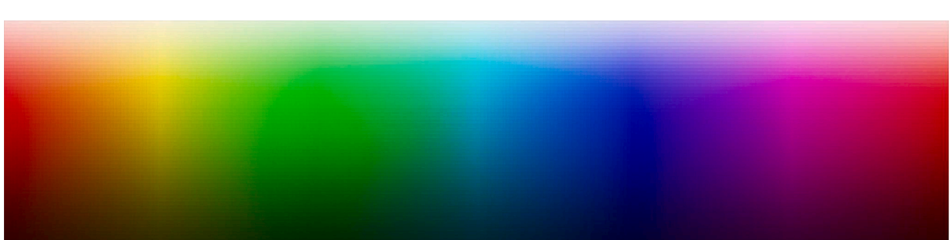


Fig. 1. Colour space used in the tasks of Experiments 2 and 3. Horizontal plane (x-coordinates) reflect variations in hue, and vertical plane (y-coordinates) reflect variations in brightness.

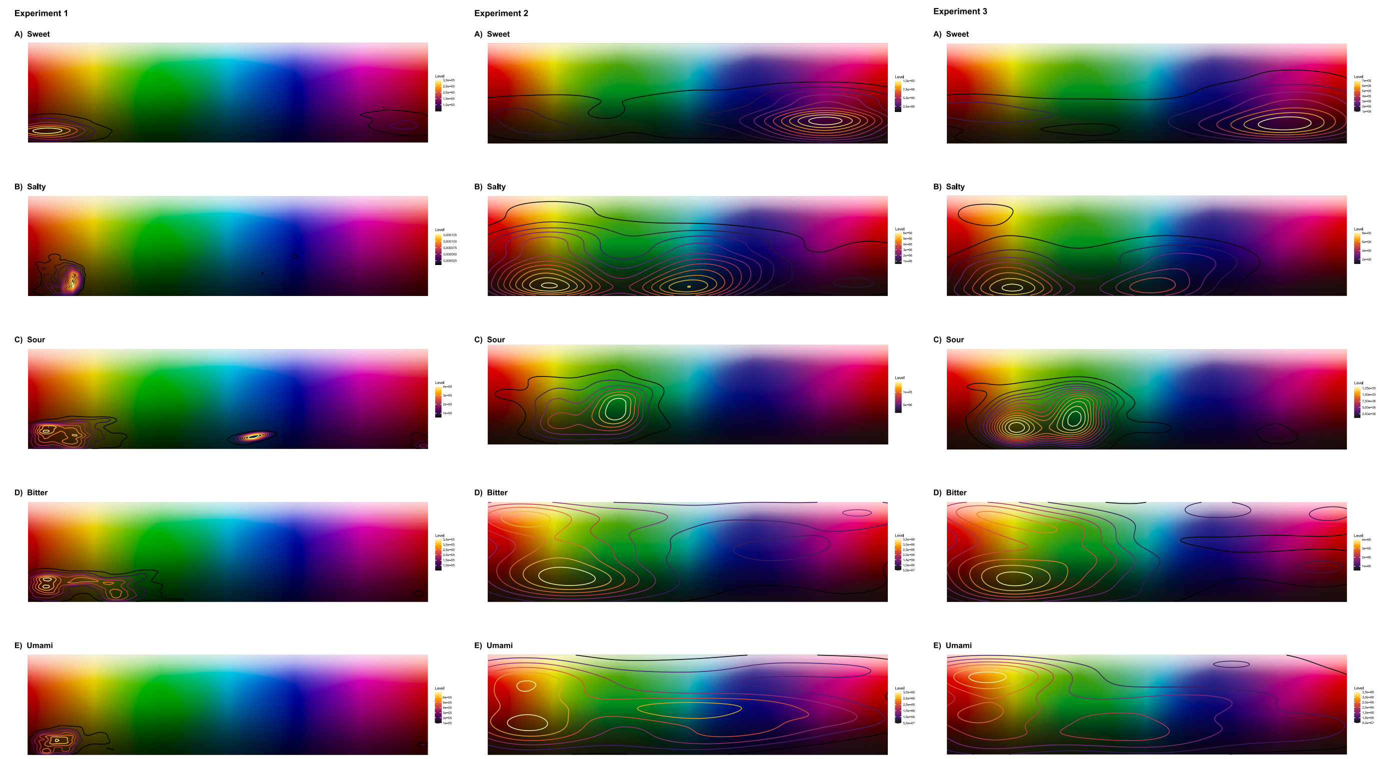


Fig. 2. 2D density plots of colour associations for each basic taste in Experiments 1 (left-hand), 2 (middle), and 3 (right-hand). Lighter and yellow contour lines represent a higher density of responses. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.3. Design and procedure

The experiment was programmed and conducted in Gorilla (https://gorilla.sc/), and only laptops or desktops could be used. In the experiment, participants were tasked with selecting the colour that they most strongly associated with each of the five basic tastes (sweet, salty, sour, bitter, and umami), presented one at a time, by clicking on the colour palette. We use taste words in the present research. They have been shown to give rise to similar patterns of results as when actual tastants are used (Saluja & Stevenson, 2018).

The participants were first introduced to the experiment and asked to provide their informed consent. Next, they were presented with detailed instructions. Subsequently, they were asked to calibrate their screen with Gorilla's built-in calibration method using a credit card. Subsequently, to familiarise themselves with the procedure, they completed a practice trial of the task, in which they had to select the colour they most strongly associated with *fatty* taste. Afterwards, the participants completed the experimental trials.

3.4. Analyses

First, two nonparametric tests for repeated measures data were performed with taste as a within-participants factor and x- (hue) and y-coordinates (brightness) as dependent variables, respectively. The Wald test for each nonparametric test were estimated using the {nparLD} R Package. Significant main effects were further analysed using the Wilcoxon Test through the {stats} R package. After that, the results were visualised via a 2D kernel estimation density plot based on all participants' colours selected for each taste and displayed the results with contours. To do this, the *geom_density_2d* function from the {ggplot2} R Package was used.

3.5. Results and discussion

A significant main effect of taste was observed for both x-coordinates, $W(4) = 145.79$, $p < .001$, and y-coordinates, $W(4) = 200.97$, $p < .001$, suggesting differences in both hue and brightness as a function of taste. The x-coordinates were significantly higher for sweetness than for the other tastes ($p < .001$). They were also higher for saltiness ($p = .038$) and umami ($p = .007$) than for sourness. No other differences were observed ($ps > 0.999$). In terms of the y-coordinates, bitterness and umami were significantly higher than saltiness, sourness, and sweetness ($ps < 0.001$), no difference was observed between bitterness and umami ($p = .110$), and sourness was significantly higher than sweetness and saltiness ($ps < 0.001$). Saltiness and sweetness did not differ significantly ($p > .999$).

In Table 1, the relative treatment effects (RTE) are presented, providing an indicator of the size of the effect. As indicated by Marmolejo-Ramos et al. (2013), the RTE denotes the likelihood that a randomly selected observation from a given subset of data is greater than a randomly selected observation from the entire dataset, and its value falls within the range of 0 to 1. The largest effect observed for the x-coordinates (hue) is for sweetness, whereas the largest effects documented for the y-coordinates (brightness) were for bitterness and umami.

The results of the 2D density plots showed that participants tended to associate different basic tastes with specific areas of the colour palette (see Fig. 2, Experiment 2). Consistent with the results of previous studies, sweetness was consistently associated with red and pink hues. However, the associated colours tended to be darker than those used in

Table 1
Relative treatment effects in Experiment 2.

Taste	x-coordinates (hue)	y-coordinates (brightness)
Bitter	0.448	0.649
Sour	0.427	0.483
Sweet	0.697	0.387
Salty	0.464	0.366
Umami	0.464	0.615

previous studies as well, as shown in Experiment 1. In addition, and also consistent with previous research, sourness was associated with green colours and, to a lesser extent, with yellows. Saltiness was associated with dark yellow and dark blue hues. The participants associated bitterness with dark yellow-greenish and light orange colours. Umami did not exhibit highly precise associations, though the participants seemed to broadly associate it with brown and green–blue hues.

Whilst these results suggest, in one way, that the colours matched to tastes in previous studies (e.g., red and sweetness) also occur when a broader colour space is used, other colours also appear (e.g., bitterness and yellow-greenish and light orange). This might be indicative of changes associated with the reference point (e.g., colour space) used by the participants to respond to the matching task. As such, in Experiment 3 we aimed to replicate the findings of Experiment 2, and we also evaluated whether participants used a specific reference object in order to guide their associations.

4. Experiment 3: Replication of matching task replication and semantic analysis

4.1. Participants

A total of 250 native English speakers from the US (122 males, 124 females, 4 other), aged 18–57 years ($M = 34.69$ years, $SD = 8.04$), took part in the study. The participants were recruited from Prolific (https://www.prolific.com/) and were compensated with GBP 0.45.

4.2. Design, materials, and procedure

Experiment 3 followed the same design and procedure as Experiment 2, with the addition of a question to assess the participants' semantic mappings underlying their colour-taste associations. More specifically, after participants selected the colour they most strongly associated with each basic taste, they were asked, in an open-ended question, what they had thought of when making that association with the specific taste (e.g., What did you think of when making this association with bitterness?).

4.3. Analyses

We conducted the same analyses and visualisations as in the previous study. Furthermore, participants' semantic mappings were analysed via a semantic network analysis. We created co-occurrence network graphs of keywords for each basic taste. First, the data was pre-processed by converting all words in participants' responses to lowercase, removing symbols, and correcting for word elongations and additional spaces. Then, participants' responses were tokenized and stop words were removed. Next, the pairwise count of all keywords was computed. To create the co-occurrence network graphs, a threshold of at least three occurrences of keyword pairs was selected. To perform the semantic network analysis, the {tidyr}, {widyr}, {textclean}, {igraph}, and {ggraph} R packages were used.

4.4. Results and discussion

The visualisation of participants' colour-taste associations revealed consistent results with the previous study (see Fig. 2, Experiment 3). As in Experiment 2, a significant main effect of taste was observed for both x-coordinates (hue), $W(4) = 111.41$, $p < .001$, and for y-coordinates (brightness), $W(4) = 189.83$, $p < .001$, suggesting, once again, the existence of differences in both hue and brightness as a function of taste quality. The x-coordinates were significantly higher for sweetness than for the other tastes ($p < .001$), and higher for umami than for sourness ($p = .048$). No other significant differences were observed ($ps > 0.071$). In terms of the y coordinates, just as in Experiment 2, bitterness and umami were significantly higher than saltiness, sourness, and sweetness ($ps < 0.001$). No difference was observed between bitterness and umami ($p > .999$). Sourness was significantly higher than saltiness ($ps < 0.001$) but not sweetness ($p = .974$). The coordinates were higher for sweetness than for saltiness ($p < .001$).

The semantic network analysis revealed that participants tended to arrive at colour–taste associations via intermediate mappings to specific entities (see Fig. 3). In the case of sweetness, two prominent patterns emerged. The participants seemed to associate sweetness with red colours because of fruits such as cherries, strawberries, and apples (though they are also green), as well as candies. In addition, they appeared to associate sweetness with pink colours because of candies. In regard to saltiness, the association with blue seemed to be driven by mappings to the ocean, whereas the association with yellow seemed to be related to potato chips/fries. For sourness, participants appeared to associate with the colour green due to apples and apple candies and with yellow due to lemons. As per bitterness, associations with brown seemed to be related to dark chocolate, whereas those with green hues were driven by vegetables, and those with yellow colours were picked up on mappings to lemons. Finally, colour associations with umami revolved around soy sauce, mushrooms, and meat.

The findings of this experiment largely replicate the results of Experiment 2, in terms of the taste-colour associations that were documented. In addition, this experiment reveals that, when asked, participants appear to base their answers on a reference object and that there are certain commonalities between said objects. To study how consistent the results of Experiment 3 are with the images found online (Experiment 1), the similarity of the content of images associated with tastes and that of images associated with specific categories appearing in the words found in Experiment 3 was determined.

5. Experiment 4: Semantic information in online pictures

5.1. Method, procedure, and analyses

Estimating content associations. First, the words from Experiment 3 were clustered to determine the most relevant categories grouping the elements that were mentioned by the participants. Before clustering, all the words that were in a plural form were replaced by their singular forms. Only food-related nouns were included, as participants also listed taste and colour-related words; this was performed manually. A total of 223 words were then grouped into 11 categories. An initial clustering was performed by applying the DBSCAN algorithm (Ester et al., 1996) using the minimum path similarity in WordNet (Miller, 1995) between two words as a distance metric, with which the number of clusters was determined. This approach was used as DBSCAN does not require to predefine a number of clusters, but it determines such a number from data. The resulting clustering included 11 clusters with the parameter epsilon set to 0.98, and a minimum of 2 data points per cluster. Afterwards, the clusters were labelled and refined manually by assigning words not in WordNet or for which the definition did not match the context of the best-matching cluster given alternative meanings of the word.

The final clusters were: Asian food, citrus, fruit, hot beverage, meat, salt, sauce, snack, soup/broth, sweets, and vegetable (See Appendix B for the words in each cluster).

Following the same procedure as for the tastes in Experiment 1, images were downloaded using the cluster names as search terms. All of the images were then compared to determine the most probable group associated with a taste image. Labelling the i^{th} image associated with a given taste as t_i and the j^{th} image in one of the defined food-related groups as g_j, we can define a distance $D(t_i, g_j)$, determining how visually different the two images are. Then, for every taste image t_i, the $\text{argmin}_j\,(D(t_i, g_j))$ is determined by taking into account the images of all the food-related groups. To compare the images, the image encoder in the CLIP model introduced by Radford et al. (2021) as a feature extractor was used. Specifically, we use the last layer of a pre-trained ViT-B/32. As a distance metric D, the normalised squared Euclidean distance was

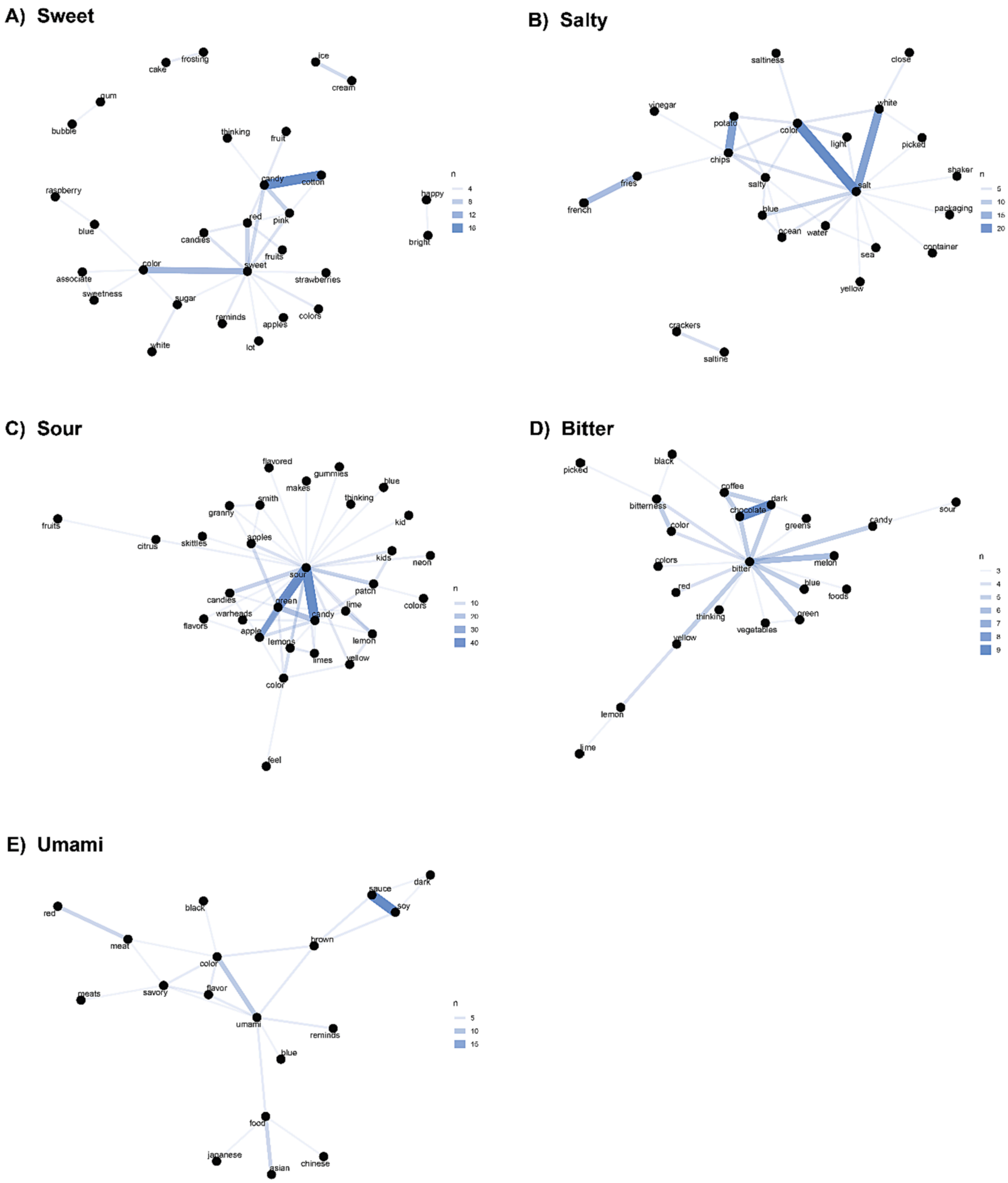


Fig. 3. Keyword co-occurrence network graphs of colour associations for each basic taste in Experiment 3. The thickness of the link between pairs of words denotes the occurrence frequency of the word pair.

used. With this information, we create a distribution over food-related groups per taste by calculating a normalized histogram of the number of images of a given taste with a minimum distance to an image in a specific food-related group.

5.2. Results and discussion

Content associations: Images associated with bitterness were visually closer, in terms of the normalized Euclidean distance, to pictures of vegetables, hot beverages, citrus and fruit. Images associated with saltiness were visually closer to images associated with snacks, and salt. Images associated with sourness were not visually similar only to images of a specific group, but rather to several different categories, mainly images of citrus, fruits, snacks, and vegetables. Images associated with sweetness were primarily similar to those of sweets, snacks and fruits. Finally, images associated with umami were visually closer to those of Asian food, soup/broth, and meat.

The results of Experiment 4 are similar to those reported in Experiment 3. The distributions over clusters per taste in Experiments 3 and 4 are presented in Fig. 4. To compare the results of these two experiments, the Spearman's correlation was calculated to determine whether the order of frequency of the elements associated with a given taste was similar between the two sets of distributions. A correlation was estimated for each taste: Bitter: $r(9) = 0.75$, $p < 0.025$, salty: $r(9) = 0.34$, $p > 0.1$, sour: $r(9) = 0.64$, $p < 0.05$, umami: $r(9) = 0.54$, $p < 0.1$, and sweet: $r(9) = 0.68$, $p < 0.05$. These results indicate similarities between the distributions, which can also be observed in Fig. 4. They are significant except for salty and umami. The main differences are attributable to more variety in the images per taste than in words. These reflect in the occurrence of sauce in pictures but not in the words from

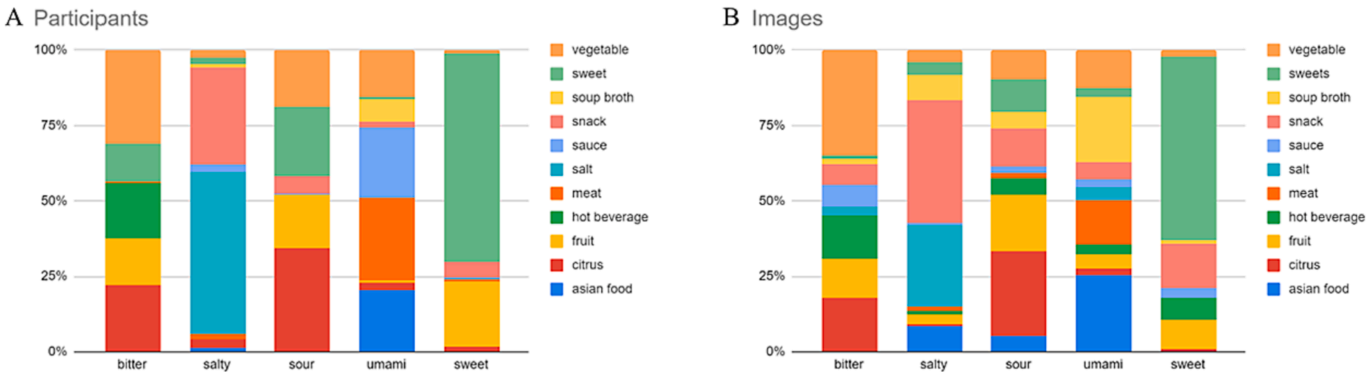


Fig. 4. Distributions over clusters per taste. A) From words in Experiment 3. B) From image similarities in Experiment 4.

Experiment 3 for the bitter taste. The same happens for Asian food and soup/broth for salty and sour. In the case of salty, the images also focus more heavily on 'snack', while words from participants are more focused on salt. Similarly, there is a higher occurrence of sauce in images than in words for umami. In sweet, the main differences are due to a higher proportion of fruit in the words and the occurrence of hot beverages in images but not in words mentioned by participants.

The results of Experiment 1–4 reveal a number of insights. First, colour-taste correspondences and source objects can be evaluated through both image processing analysis and matching tasks. Second, the colours that correspond to specific taste categories are more varied than documented before. Third, people appear, to a certain degree, to match the colours that correspond to a specific source object, which may help to explain the level of variability in the data. Assuming that the associative learning account of taste-shape correspondences is correct to a certain degree, it is reasonable to expect variations in the data as the saliency of objects involving colours and tastes that people are exposed to can vary. As such, patterns of association may build on a number of dynamic changes in people's environments. For example, fruits, which were a common object mentioned in the matching tasks, and which appeared in the image processing analysis, also change over time, and people may interiorize these regular transformations. To further evaluate the associative learning account of taste-colour correspondences, in Experiment 5, we evaluate the extent to which changes in the ripening process of fruits relate to variations in the colours and tastes attributed to the fruit. The reason for exploring this is that variations in fruit ripening can involve changes in both colour (e.g., green, red) and also taste (sour/bitter, sweet; Foroni et al., 2016; Maga, 1974).

6. Experiment 5: Internalization of statistical regularities

6.1. Participants

A total of 201 native English speakers took part in the study. Nevertheless, data from four participants with incomplete or erroneous answers (e.g., answer age with a string of characters) were removed from the analyses. The final sample consisted of 197 participants (97 he/him, 97 she/her, 2 they/them, and 2 other) aged 18–80 years (M = 39.70 years, SD = 14.44). Participants were recruited from Prolific (https://www.prolific.com/) and were compensated with GBP 0.67.

6.2. Design, materials, and procedure

The experiment was programmed and conducted on Qualtrics (https://qualtrics.com). The study followed a one-way repeated measures designed with factor fruit stage (unripe, ripe, and overripe). The dependent variables were colour coordinates (see Fig. 5), and tastes (sweet, sour, salty, bitter, and umami) and liking. Note, though, that the alternatives given to the participant were only a subset of those in the previous experiments, considering the areas that the associations covered.

At the beginning of the experiment, the participants were asked to report their age, gender, and frequency of fruit consumption (daily, 4–6 times a week, 2–3 times a week, once a week, less often, I don't eat fruit). Followed by that, the participants were presented with three fruit stage conditions in a random order. In this part of the study, the participants were told "Imagine an [unripe OR ripe OR overripe] fruit and answer the questions following." The first question consisted of indicating the colour that they associated with the fruit by specifying the coordinates in the colour space (see Fig. 5). After that, the participants were asked to evaluate how they associated the tastes with the fruit, and the extent to

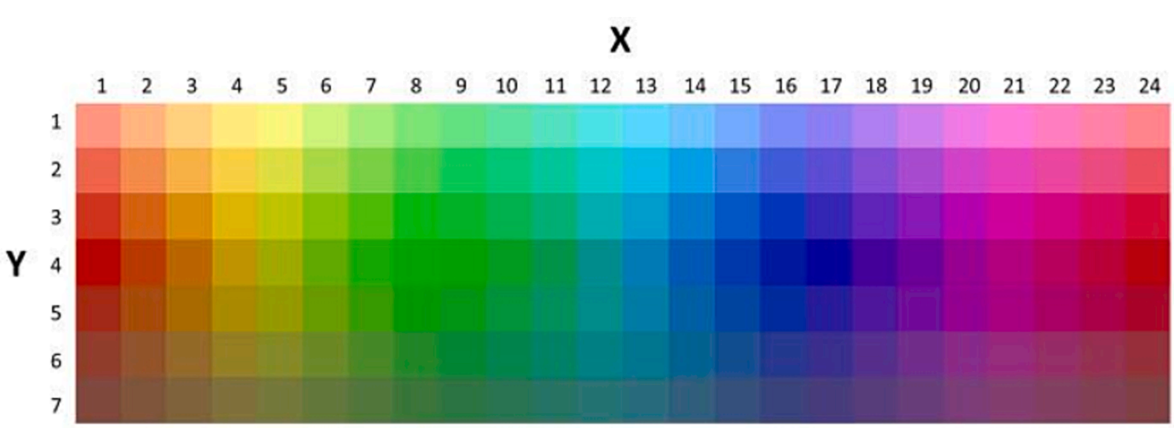


Fig. 5. Colour space used in the tasks of Experiment 5.

which they thought they would like the fruit. These variables were measured in 10-point visual analogue scales. Finally, the participants were asked whether they have thought of a specific fruit during and to report it.

6.3. Analyses

To analyse the results, several robust one-way analyses of variance–type statistic (ANOVA-type statistic) were conducted with ripening stage as factor, and × and y colour coordinates, as well as tastes, as dependent variables. The analyses were conducted in the R statistics environment, via the {nparLD} package.

6.4. Results and discussion

The stage of fruit ripening exerted a significant influence on all variables (see Table 2). The values for hue were lower for the overripe stage relative to the ripe and unripe ones (*ps* < 0.002), though no difference was observed between the ripe and unripe stages (p =.180). In contrast, the values for brightness were lower for the overripe stage relative to the ripe and unripe stages (*ps* < 0.001). No difference was observed between the ripe and unripe stages (p =.150, see Fig. 6, for a visualization of the colour associations).

The sweetness and liking ratings were higher for the ripe, followed by the overripe, and finally the unripe stage (*ps* < 0.027). The sourness and bitterness ratings were higher for the unripe, followed by the overripe, and the ripe stage (*ps* < 0.001). In terms of the salty ratings, the ratings were higher in the overripe and unripe stages than in the ripe stage (*ps* < 0.035), while no difference was observed between the overripe and unripe stages (p >.999). We also performed correlations between the variables in order to assess the relationship between them (see Appendix A).

These results suggest that the ripening stage of fruits influences both colour and taste perception. This study provides initial support for the idea that the way in which a fruit changes might involve both colour and taste information in a way that matches, but only to a certain degree, colour-taste correspondences. Indeed, overripe differed from ripe and unripe in terms of colour but no difference was found between ripe and unripe. However, taste perception did change. Ripe fruits were perceived as significantly sweeter than the others and unripe as significantly more bitter and sour than the others. These results suggest that colour-taste correspondences might rely on specific identities or meanings for taste-shape correspondences more strongly than specific within-object variations.

One possible limitation of this study though is the fact that people might have relied on specific fruits while responding to the task (e.g., Foroni, Pergola, & Rumiati, 2016). Whilst we wanted to capture the overall sense that people might have of fruits at different ripping stages, we cannot rule out this. For example, some fruits do not have as much of a visually transparent ripening process such as like watermelon (where other factors may play a role, such as size) compared to bananas (at least externally, before opening the fruit).

Table 2
One-way ANOVA-type statistics associated with the x- (hue) and y-coordinates (brightness), as well as each of the tastes, as a function of fruit ripening stage, in Experiment 5.

Variable	ANOVA			RTEs		
	df	W	*p*	Unripe	Ripe	Overripe
x coordinates – Hue	2	73.08	<0.0001	0.614	0.483	0.403
y coordinates - Brightness		145.78	<0.0001	0.445	0.390	0.666
Sweet		459.41	<0.0001	0.252	0.683	0.565
Sour		96.60	<0.0001	0.630	0.385	0.484
Salty		18.35	0.0001	0.513	0.460	0.527
Bitter		207.42	<0.0001	0.660	0.343	0.497
Liking		636.61	<0.0001	0.334	0.785	0.381

7. General discussion

The present research focused on replicating and extending research on colour–taste correspondences by using new analytical methods that would reveal a more fine-grained understanding of taste–colour correspondences. In addition, it focused on investigating the potential role of the associative learning account in these correspondences and whether people use source objects and variations captured in the statistical regularities in of food contexts to guide their associations. While the research has documented crossmodal correspondences between tastes and colour hues, there is still a need to clarify why people associate these features. Spence and Levitan (2021) outlined several possible mechanisms, including crossmodal similarity, associative learning, and emotional mediation. Overall, the findings suggest that the statistical account may play a key role in the formation of certain taste–colour correspondences at the object category level (e.g., fruits), but not necessarily at the case-specific level (e.g., banana), and that such regularities would seem to be present in those online images that are associated with tastes. However, other factors are likely also at play.

Five experiments were conducted to revise, replicate, and extend previous findings on colour–taste correspondences, evaluating the relationship between specific food categories and colours, and assessing people's colour and taste associations with fruits at different stages of the ripening process. The experiments used image processing analysis, colour–taste matching tasks, and questions to assess whether specific source objects guided associations. The results of Experiment 1 revealed that those online images associated with sweetness tend to have predominantly red hues, while salty tastes are associated with yellow and orange hues. Sourness was associated with dark oranges, yellows, and reds, and bitterness was associated with a broader range of hues, including green, yellow, orange, and red. Umami was associated with brighter reds and dark browns. Experiment 2 found that participants tended to associate different basic tastes with characteristic colours ranges, that is, sweetness with red and pink hues (darker than previous studies, Spence and Levitan, 2021), sourness with green and yellow hues, saltiness with dark yellow and dark blue hues, bitterness with dark yellow-greenish and light orange hues, and umami with brown and green–blue hues.

The results of Experiment 3 revealed that participants arrived at colour–taste associations via intermediate mappings to specific object entities. Sweetness was associated with red and pink colours due to fruits and candies, while saltiness was associated with blue and yellow colours due to the ocean and potato chips/fries, respectively. Sourness was linked to green and yellow due to apples and lemons, while bitterness was associated with brown and green due to dark chocolate and vegetables. Umami was broadly associated with foods such as soy sauce, mushrooms, and meat.

The results of Experiment 4 revealed that different tastes were associated with different types of images. Bitterness was found to be associated with hot beverages, vegetables and citrus, while saltiness was associated with snacks and salt. Sourness had broader associations with citrus, fruits, snacks, and sweets, while sweetness was mainly associated with sweets, snacks and fruits. Umami was associated with Asian soup, broths and meat. Furthermore, the results were compared to those of Experiment 3, and the outcome indicated that the order of frequency of the elements associated with tastes are congruent between the images found online, and the answers from participants, except for salty and umami.

Finally, the results of Experiment 5 revealed that the stage of fruit ripening (i.e., unripe, ripe, overripe) had a significant influence on the colours and tastes associated with the fruit. Hue values were lower for overripe fruits compared to ripe and unripe ones, while brightness values were higher for overripe fruits. Sweetness and liking ratings were higher for ripe fruits, while sourness and bitterness ratings were higher

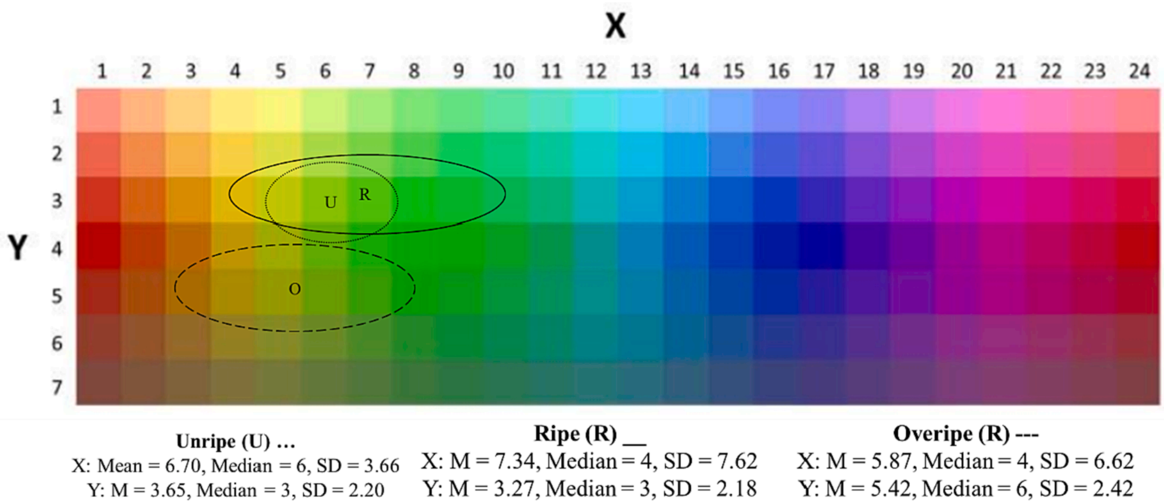


Fig. 6. Colour – fruit ripening state associations in Experiment 5. The letter represents the average of the stage of the fruit as a function of X (hue) and Y (brightness) and the ellipses represent the corresponding standard deviation.

for unripe fruits. Salty ratings were higher in the overripe and unripe stages compared to the ripe stage.

In general, these results replicate previous research on taste-colour correspondences (e.g., Saluja & Stevenson, 2018; Spence & Levitan, 2021; Velasco et al., 2016) and extend them by providing a more fine-grained hue and brightness scale. For example, Motoki, Takahashi, and Spence (2021) found that coffee shop images with reddish and lighter colours were linked to sweeter coffee expectations, while greenish and darker images were associated with more bitter/tasty coffee expectations (see also Huang et al., 2019, 2020).

Our results suggest that the assessment of colour–taste correspondences and source objects can be conducted using both image processing analysis and matching tasks. Notably, the findings revealed a greater variety of colours associated with specific taste categories than previously reported. What is more, our study provides, to the best of our knowledge, for the first time, a clear link into the sort of object categories that may guide said associations (Experiments 2–4). Individuals exhibited a tendency, to some extent, to match colours corresponding to specific source objects, which potentially accounts for the observed data variability. Assuming the potential validity of the associative learning theory regarding taste-shape correspondences, it is reasonable to anticipate fluctuations in the data due to variations in the saliency of colours and tastes to which individuals are exposed. Consequently, patterns of association could arise from the dynamic changes present in people's environments. Whilst Experiment 5 offered preliminary evidence supporting the notion that the transformation of a fruit involves the perceptual integration of colour and taste information, it only aligned to a certain degree with the colour-taste correspondences documented in previous research. These findings suggest that colour-taste correspondences may rely more heavily on specific identities or meanings associated with taste-shape correspondences rather than variations within them.

Whilst the various results presented here are indicative of an associative learning mechanism of this type of correspondence (Higgins & Hayes, 2019), we cannot rule out other potential explanations. Indeed, recent research on colour–odour correspondences suggests that colour-odour matching is not affected by verbal interference and that odour-colour matches are more accurate for familiar scents and correctly identified odours (Speed et al., 2023). This led Speed and her colleagues to propose that semantic associations play a role in odour–colour associations, but the act of labelling an odour in the moment does not seem to have a significant impact. As such, other mechanisms may be involved in the matching process. This is, perhaps, something that may inform the results of the present study. Although we can observe that associative learning appears, to a great extent, to guide their associations, this might not necessarily be the only mechanism at play (see also Barbosa Escobar et al., 2023, for another example in the context of temperature-based correspondences).

The implications of these findings suggest that colour plays an important role in shaping our perceptions of taste. Marketers and food manufacturers may benefit from understanding the colour-taste associations and using them in their product design and packaging (Velasco and Spence, 2018). Moreover, chefs and food designers can use colour to create visually appealing dishes that enhance the perception of taste (Spence et al., 2022). Understanding the impact of fruit stage on colour and taste could also inform decisions about when to harvest fruit for optimal flavour. Furthermore, our results can inform potential solutions leveraging colour-taste crossmodal effects and their relationship with ripening stage to reduce food waste of aesthetically imperfect fruits (van Giesen & de Hooge, 2019). Overall, the results of the present study highlights the complexity of the relationship between taste and colour and the importance of considering both factors in the design and consumption of food.

7.1. Limitations and future directions

Several limitations should be acknowledged in this study. First, the participants were from a specific country, and online images were linked to the same location. Hence, if colour-taste associations were to exhibit some degree of variation across different countries/cultures, especially when these associations are mediated by source objects, a cross-country study would be expected to highlight this. This, too, suggests that future research might aim to evaluate the effect of source objects that come up in the searches, with broader and more extensive images, in order to assess object- or context-specific colour-taste correspondences. Second, the colour palette that participants in the different experiments were exposed to may not have been strictly the same, as screens differ in the extent and accuracy of the gamut of colour that they can display. Nevertheless, to precisely control for colour accuracy requires screens with colour accuracy certifications (e.g., Adobe RGB), which limits the sample size of any potential experiment. Third, saturation, which is another key colour feature, was not evaluated as a factor and as such, future research may look at taste-colour saturation associations capitalizing on the methods presented here.

Such limitations can also be connected to the differences encountered among Experiments 1–3. The colours found in Experiment 1 are consistent with those in Experiments 2 and 3 in most cases. Yet, the results might differ significantly as the exact mapping of hue values from pixels in images does not consider the possible variability in the perceptual mapping between colour associations and colour choices that participants make. So, for example, certain shades of red or pink associated with sweetness can be linked to many hue values by participants and are particularly centred on the left area of the colour palette they were presented with, yet the actual values in images map to other areas of the palette that can also be semantically associated with red colours. This makes the comparison more difficult given that the mappings are not equivalent and might be measuring different attributes.

Moreover, those differences can imply that the representation in terms of hue is not aligned with the actual colour perception of participants, which would make using colour categories more meaningful than hue values for these comparisons. On the other hand, the results of Experiment 4 align with those of Experiment 3. So, the objects that people associate colours with are consistent with those in images related to specific tastes. That suggests that the observed intermediate mappings are more consistent than colours, possibly because the mapping to a single colour is not optimal given the different hues an object might have, while food categories are more consistent and stable. This might imply that asking participants about the food items they associate with specific tastes, and then analyse the colours in images associated with those objects might indicate the taste-colour associations better, or at least in a more stable way, than directly asking participants about colours they associate with taste.

CRediT authorship contribution statement

Carlos Velasco: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **Francisco Barbosa Escobar:** Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Charles Spence:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Juan Sebastian Olier:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing.

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.

Data availability

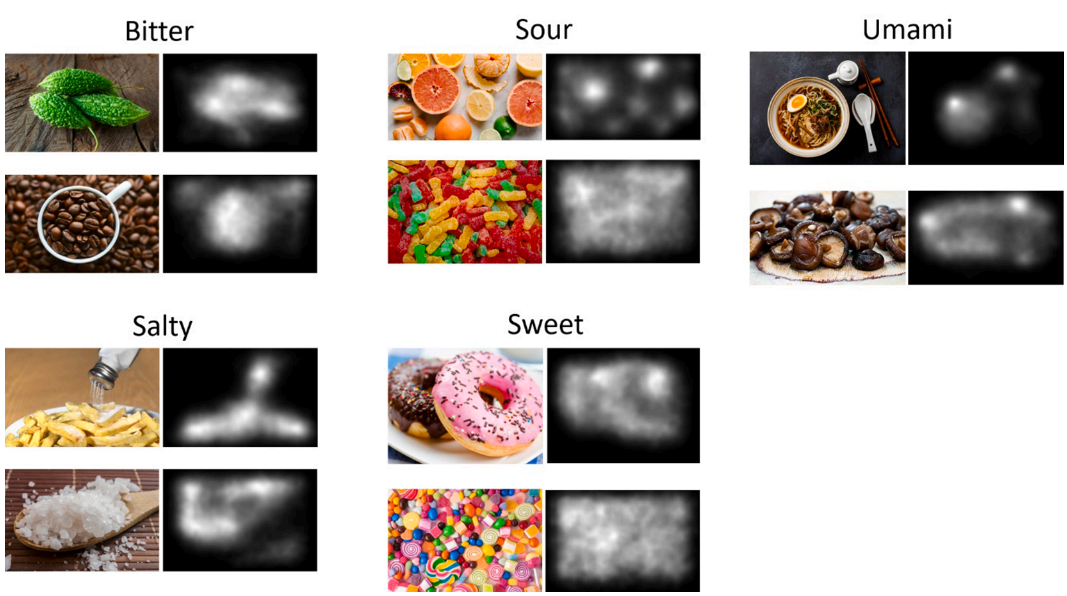
Data will be made available on request.

Acknowledgements

We would like to thank the Research Fund of the Department of Marketing, BI Norwegian Business School, for funding the data collection of the experiments. In addition, we would like to thank Sophie Donohugh, for her support with the execution of Experiment 5.

Appendix A

Sample images per taste gathered for Experiment 1, and the corresponding estimated saliency maps.



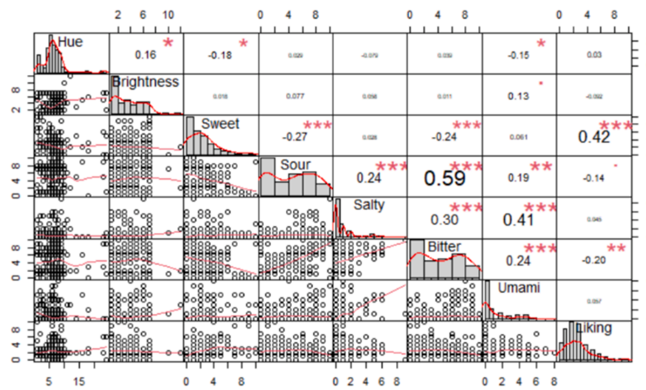
Appendix B

Words included in clusters in Experiment 4.

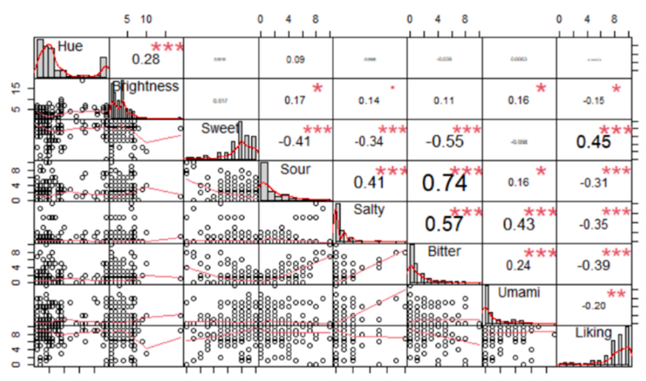
Asian food	sushi, Asian, Japanese, seaweed, Chinese, wasabi
Broth	miso, broth, soup, ramen
Citrus	grapefruit, lemon, orange, lime
Fruit	cherry, berry, raspberry, strawberry, fruit, melon, apple, grape
Hot Beverage	coffee, tea
Meat	meat, roast, fish, steak, chicken, beef, meaty
Salt	salt
Sauce	soy, sauce
Sweet	sugar, cake, sweet, tart, candy, dessert, pie, cotton, cupcake,donut, brownie, lollipop
Vegetable	green, arugula, vegetable, kale, broccoli, brussel sprout, kale, leaves, leafy, pickle, mushroom, bitter melon, broccoli

Appendix C

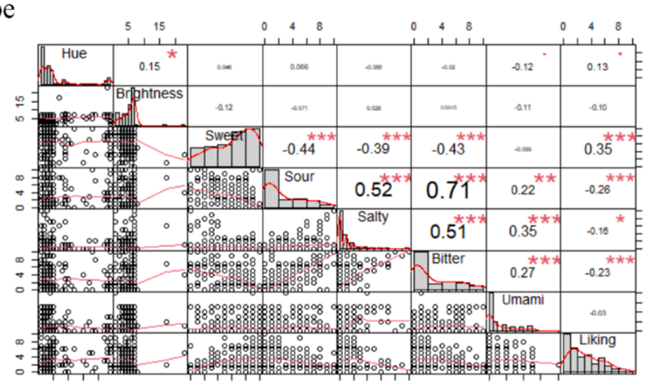
A) Unripe



B) Ripe



C) Overripe



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