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Exploring the Links between Colours and Tastes/Flavours†

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Abstract. *The colour and other visual appearance properties of food and drink constitute a key factor determining consumer acceptance and choice behaviour. Not only do consumers associate specific colours with particular tastes and flavours, but adding or changing the colour of food and drink can also dramatically affect taste/flavour perception. Surprisingly, even the colour of cups, cutlery, plates, packages, and the colour of the environment itself, have also been shown to influence multisensory flavour perception. The taste/flavour associations that we hold with colour are context-dependent, and are often based on statistical learning (though emotional mediation may also play a role). However, to date, neither the computational principles constraining these ubiquitous crossmodal effects nor the neural mechanisms underpinning the various crossmodal associations (or correspondences) that have been documented between colours and tastes/flavours have yet been established. It is currently unclear to what extent such colour-taste/flavour correspondences ought to be explained in terms of semantic congruency (i.e., statistical learning), and/or emotional mediation. Bayesian causal inference has become an increasingly important tool in helping researchers to understand (and predict) the multisensory interactions between the spatial senses of vision, audition, and touch. However, a network modelling approach may be of value moving forward. As made clear by this review, there are substantial challenges, both theoretical and practical, that will need to be overcome by those wanting to apply computational approaches both to understanding the integration of the chemical senses in the case of multisensory flavour perception, and to understanding the influence of colour thereon.*
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1. INTRODUCTION

Eating and drinking are amongst life's most multisensory experiences (see [136], for a review). Indeed, according to eminent neuroscientist Gordon Shepherd, flavour perception (e.g., when wine tasting) engages more of the human brain than most activities [123]. Visual information has been shown to influence our expectations concerning the sensory properties of food and drink, with colour acting as a particularly salient sensory cue (e.g., [50, 137]). It has long been suggested that "we eat first with our eyes" [5], and visual cues can dramatically influence both the palatability of food as well as its perceived taste, aroma/odour, and flavour [29, 153, 159, 189].

1.1 *Outline of Review*

In this narrative review, the behavioural/psychophysical evidence demonstrating that colour, no matter whether or not it happens to be a property of a food or beverage product itself, or else product-extrinsic (e.g., as in the case of coloured cups, plates, packaging, environments, etc.), influences various aspects of taste/flavour perception is critically evaluated. We discuss various approaches to conceptualizing colour's influence over taste/flavour, including Ecological Valence Theory [86], Colour-in-Context Theory [34], the increasingly-popular Bayesian Decision Theory (see [59, 70]), and suggest a network modelling approach as a potential future computational direction for the field. We briefly summarize the limited evidence concerning the neural underpinnings of colour-flavour interaction, highlight a number of the problems that are associated with trying to model colour's influence over taste/flavour perception, and offer guidance for future research.

1.2 *Terminology and Basic Neural Mechanisms of Multisensory Flavour Perception*

For the purposes of this review, taste refers to the information that is transduced via the gustatory receptors primarily located on the tongue (e.g., coding sweet, sour, bitter, salty, and umami), whereas flavour refers to the multisensory experience that results from the combination of retronasal olfactory, taste, trigeminal, or common chemical [20, 57] sensory information when available (e.g., as when we talk of strawberry or coffee flavour [156]). One of the potentially important distinctions when considering aroma/flavour perception is between orthonasal and retronasal olfaction (see [106, 193]), with orthonasal olfaction associated with inhaling/sniffing, whereas retronasal olfaction occurs when volatile rich air is pulsed out from the back of the nose when we chew and swallow (see also [78, 127]). Orthonasal olfactory cues thus help set our flavour expectations, whereas retronasal olfaction is considered constitutive of multisensory flavour perception (see [134, 156]). Trigeminal inputs occasionally contribute to multisensory flavour perception [182]. Flavour perception is thus one of the most multisensory of our daily experiences. Neuroimaging research in which participants were shown pictures of their

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favourite foods while lying in the brain scanner demonstrates that the anticipation of food when we are hungry leads to a marked increase in cerebral blood flow [189]. Interestingly, however, once people start to eat brain activity is often observed to decline significantly (see also [130] and [179] for a review and meta-analysis). Such research hints, then, at the importance of vision in terms of helping to set our flavour expectations.

The last few years have seen a rapid growth in our understanding of the neural networks that underlie multisensory flavour perception (see [122, 126] for reviews). Gustatory stimuli are known to project from the tongue to the primary taste cortex (more specifically, the anterior insula and the frontal or parietal operculum [166]), whereas olfactory stimuli project directly to the primary olfactory (i.e., piriform) cortex. From there, the inputs from both senses project to the orbitofrontal cortex (OFC). Gustatory stimuli project to caudolateral OFC whereas olfactory stimuli project to caudomedial OFC. The OFC plays a central role in representing the pleasantness (and reward value) of food and drink [126]. Dana Small and her colleagues presented familiar/unfamiliar combinations of retronasal olfactory and gustatory stimuli to participants [131], observing superadditive neural interactions (see [168]) in the OFC for familiar (or congruent, sweet–vanilla), but not for unfamiliar (or incongruent) combinations of stimuli (such as for the salty–vanilla combination; see also [32, 191]). Several other areas—including the dorsal insula, the frontal operculum and the anterior cingulate cortex—also showed increased neural activity, thus constituting what could perhaps be thought of as a 'flavour network' ([122, 126, 128]).

2. CROSSMODAL INFLUENCES OF COLOUR ON FLAVOUR

A long history of research has investigated the impact of adding and/or changing the colour of food and (more commonly) drink on taste/flavour perception (see [137, 139], for reviews), as well as on hedonic responses [200]. Separately, however, researchers have also been interested in the more abstract crossmodal correspondences demonstrated between colour patches or colour words and tastes, aromas, and/or fully-fledged flavours [99, 155, 184]. Crossmodal correspondences have been defined as the sometimes surprising associations that we all experience between seemingly-unrelated sensory features in different sensory modalities (see [133, 144] for reviews). Such correspondences could arise as a result of similarities in the neural coding of the corresponding stimuli, the statistical co-occurrence of sensory features in the environment, and/or the use of the same linguistic/semantic terms to describe different sensations. There is, however, also growing evidence for the emotional mediation underlying many crossmodal correspondences, such as in the case of the crossmodal matching of music and visual stimuli including colours or paintings [87, 148]. Emotional mediation has also been shown to play an important role in the crossmodal matching of colours with odours (see [113]; see also [149] for a recent review). That said, the cognitive/neural mechanisms underlying crossmodal correspondences with colour that involve taste and flavour (olfaction) may not necessarily be the same.

While significant effects of adding/changing the colour of food and drink have been reported in many studies, no significant results have been reported in certain others (e.g., see [138] for a review). As such, the empirical research that has been published to date has been somewhat unclear as to the precise conditions under which changing the colour modifies the taste and/or flavour of food and drink. One attempt to explain the inconsistency in the literature on food colouring was put forward by Shankar and her colleagues [119–121]. These researchers highlighted how people often have (or internalize) different flavour (aroma) associations with specific colours. For example, Europeans typically associate the smell/flavour of cinnamon with the colour brown (i.e., their association is with the dried spice) whereas North Americans often tend to associate it with the dark red of the hard-boiled cinnamon-flavoured sweets instead (cf. [30, 64, 109, 118, 132]). In other words, the colour associations that people hold with aromas or flavours may differ. Shankar et al. [119] conducted a series of studies showing that the degree of discrepancy between the aroma/flavour of a coloured drink, and the flavour that participants associated with that colour, determined whether or not, and how exactly, the colour of the drink biased the participant's identification of its aroma. When the discrepancy was small, assimilation (or visual dominance) was observed. When the discrepancy was larger, however, the colour cue was seemingly ignored. Given that most of what we think we taste we actually smell (via retronasal olfaction; see [138] for a review), Shankar et al.'s 'degree of discrepancy' account of coloured aromas should likely also apply in the case of colour's influence over flavour perception (though see [61]).

Cultural differences in how ingredients are used in cuisine may also influence taste and flavour expectations. In the US, for example, pumpkin is often used in the context of sweet foods (e.g., pumpkin pie, pumpkin spiced latte Frappuccino at Thanksgiving), whereas it is more typically considered a savoury ingredient in other parts of the world (see also [14], on the differing cultural associations with nutmeg, and on the cultural differences in the basic tastes that are associated with food, or rather with the aromas of various spices). Within the literature on both colour and olfaction, the evidence suggests that when multiple possible associations are consistent with a specific colour or odour stimulus, people's preferences are better predicted by a model that uses a weighted average of all of people's individual preferences for the associated objects than are those preferences that are based on a single-associate model (e.g., [86, 114]). When people's own idiosyncratic object associations (e.g., a colour might remind someone of their favourite sweater) are included, as well as "standard" associations generated across a group (e.g., the colour blue for the sky), the model's fit improves still further; thus further reinforcing the role of experience in developing associations [115, 116].

One might wonder whether this approach, known as 'Ecological Valence Theory' [86] could also be extended to help predict the crossmodal correspondences that have been documented between colours and odours/tastes, and not just people's hedonic preferences within a sense. Here, it is perhaps worth noting how the colours that synaesthetes associate with letters have been shown to be predictable, at least in part, based on the colours of the objects that they happen to associate with words that start with the letter. So, for example, the letter 'A' is often associated with 'Apple', with apples typically being green or red [71], thus perhaps explaining the varying colour associations that have been reported in this particular case.

Over the years, a number of researchers have suggested that the phenomenon of sensory dominance might help to explain (or at the very least to describe) the crossmodal influence of colour upon people's taste/flavour judgments [197, 198]. As a case in point, according to Zampini and his colleagues, the flavour that is associated with the colour of a food or drink product will sometimes determine (or dominate) the experienced taste/flavour (see also [33] and [135], for a developmental angle to sensory dominance in the world of multisensory flavour perception). Complete visual dominance is by no means always the outcome that has been observed in the literature. There is sufficient evidence to show that adding/changing the colour of a food or drink can sometimes result in the experience of flavours that are neither present in the food nor drink itself, nor necessarily associated with the colour, but emerge from the integration of visual flavour expectations with chemosensory cues [188]. Wang and Spence demonstrated the impact of adding colour in a study on the perceived aroma/flavour of a white wine that had been artificially coloured to look like a rosé wine when compared to the ratings given for unadulterated white and rosé wines (see Figure 1, for a summary of the results). The study was conducted in a large group of participants ($N = 168$) having different levels of expertise in the world of wine. The participants tasted three wines—a white wine, a rosé wine, and the white wine dyed to match the rosé (the fake wine in Fig. 1). The participants selected three aroma and three flavour descriptors from a list of descriptors. They also rated their liking for the wine, flavour intensity, and how difficult they found it to describe each wine. Linguistic analysis of the results revealed that those with wine tasting experience judged the miscoloured wine to be much more similar to the rosé than to the white wine, even though the fake wine and the white wine were one and the same. As can be seen in Fig. 1, red fruit descriptors were attributed to both of the rosé-coloured wines, especially in terms of flavour. Quantitative ratings revealed that the miscoloured wine was liked less than either the white or rosé wines. The participants also found it more difficult to describe the miscoloured (or fake) wine than they did to describe the rosé wine. Notice how tropical fruit aromas were only really perceived in the miscoloured wine condition. Such 'emergent' responses can therefore be taken to suggest that the flavours we perceive result from some sort of combination (or integration) of the unisensory cues. However, understanding the nature of that combination is by no means straightforward.

2.1 *On the Multiple Tastes/Flavours that are Associated with Colours*

Even at individual level, the same colour may be associated with a variety of different tastes and flavours, depending on the context in which it happens to be presented. So, for example, although red in fruit typically indicates (and is associated with) sweetness, it may also be associated with the spiciness of chili peppers (which are, after all, also fruits; [124, 145, 176]). Perhaps more fundamentally, therefore, redness in the case of fresh produce might be associated with ripeness, (note that it has been suggested that trichromatic colour vision in primates may have evolved specifically to help detect the ripe fruits from amongst the verdant green forest canopy [173, 174]), as much as with any specific basic taste or oral sensation [40, 62]. Certain natural food colours, especially those on the blue/purple end of the colour spectrum, tend to be correlated with a high phytonutrient content (see [95, 153]). (There is also a separate line of research suggesting that it is the energy density/fat content of foods that is what the brain really cares about most, and thus pays attention to [9, 44, 75, 175].) One intriguing question here concerns what, exactly, the relation is between the strength and ambiguity of the colour-flavour mapping (cf. [102]). The notion of consensuality (referring to the degree of agreement between observers for statements that may have no objectively correct answer) potentially becomes relevant here [60].

Meanwhile, in the case of processed foods, people might legitimately associate blue food colouring with the flavour of orange (blue curacao), raspberry (cotton candy, slushies), or mint (think mouthwash) [118, 142]. Hence, the taste/flavour that is primed by food colour often depends on the context, or food format, in which that colour happens to be presented or seen. Wan and her colleagues [184] demonstrated how the flavour expectations elicited by a transparent coloured drink depend, at least in some small part, on the glassware in which that drink is presented (see Figure 2). The participants were shown (online) pictures of transparent coloured liquids in a range of different clear glassware and asked what flavour they expected a drink having that colour would have. Even though the glassware was irrelevant to the participants' task, it nevertheless sometimes biased their judgments. As such, the glassware in which a drink is presented can be considered as a kind of contextual cue. Notice here also how presenting such coloured transparent drinks, as has been done in the majority of published research on food colouring, tends to minimize the impact of other visual cues, such as, for example, those related to the shape or texture of the food. The meaning of colour in food is often constrained/altered by the format—e.g., just think about how the same colour may set quite different flavour expectations if it is seen in the context of rice, yoghurt, jelly, or cake (e.g., [33, 46, 56, 74]). One

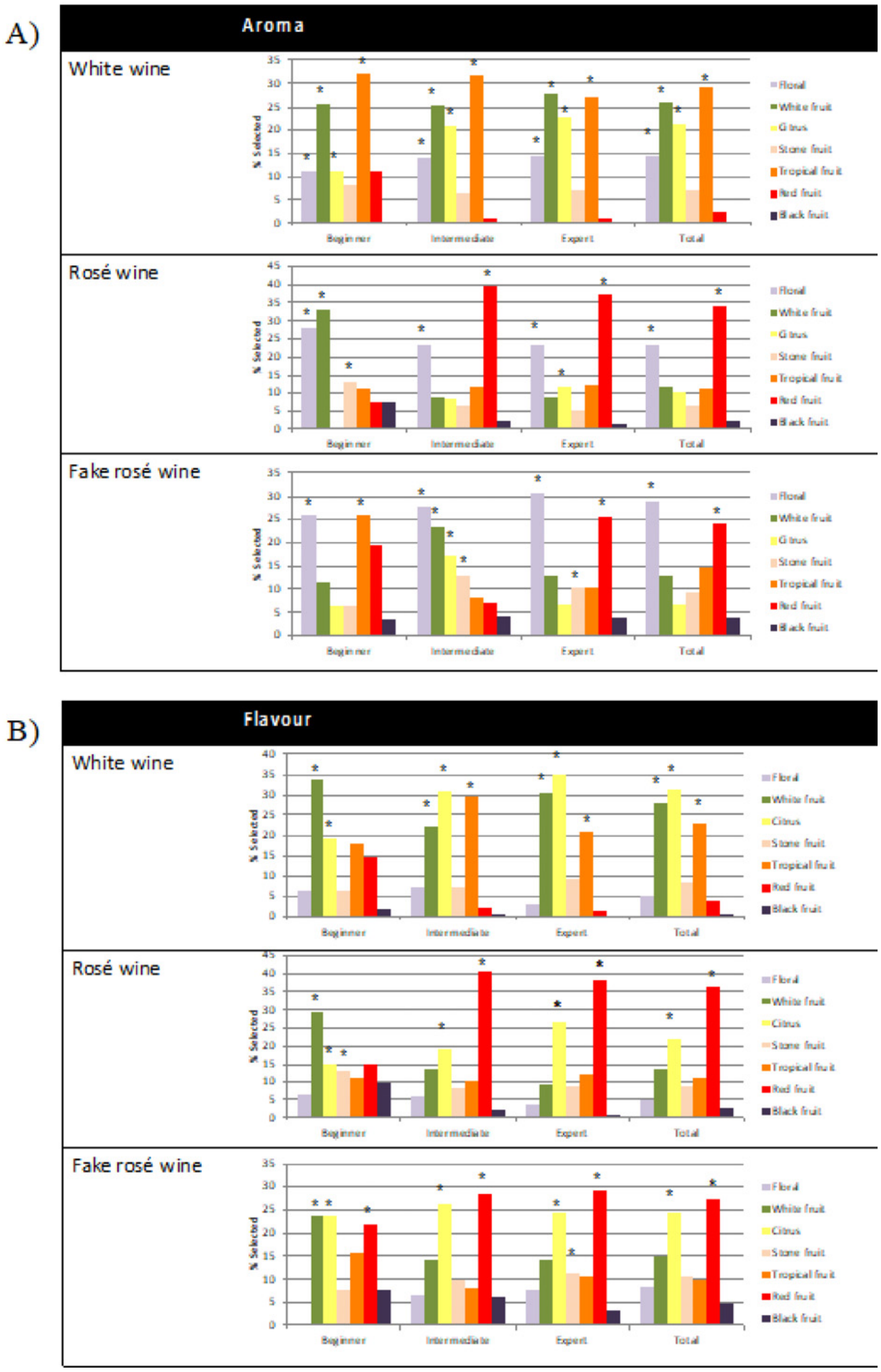

Figure 1. Distribution of (A) aroma and (B) flavour descriptors for three wines, sorted by the expertise level of the participants (Beginner, Intermediate, and Expert). Note that the right-most columns show the average across participant groups. The Fake rosé wine condition is the one in which the white wine was miscoloured pink. Distribution is normalised as the percentage of the total number of descriptors selected for a particular wine and by the particular set of participants. Asterisks indicate where the descriptor group (e.g., 'Floral') was selected significantly above chance level. Reprinted from [33].

way in which to perhaps understand such phenomena is to build upon 'Colour-in-Context' Theory [34] (see also [100]), according to which the meaning, or association, we hold with colours depends upon the context in which they are presented. As we have just seen, the context can be determined by, or may relate to, a host of factors including everything from glassware to format of food to situation (e.g., bathroom or bar will likely change the expected flavour of a blue drink: see [107, 142]).

Intriguingly, blue was rated as the second sweetest drink colour by the more than 5,000 people who took part in a study in which they were asked to pick which of six drinks looked the sweetest [180] (see Figure 3). The participants who took part in this study either took part online, or at

Figure 2. The four different glasses in which coloured drinks were presented to participants in a series of cross-cultural studies designed to assess the impact of glassware on the flavour expectations set by coloured drinks [184]. The drinks could have one of seven colours (blue shown).

London's Science museum as part of a Cravings exhibit. The participants came from diverse backgrounds and from every continent. There was also a very wide age distribution. At this point, one might want to know whether blue is associated with sweetness directly, or whether instead it might actually be associated in the minds of many people with a raspberry flavour, and is it the latter that is associated with sweetness? One could, then, think of the colour-taste association as being mediated by flavour. As yet, however, we are not aware of anyone having conducted such a mediation analysis to better understand colour-taste/flavour interactions. The history of the blue raspberry flavour [88] is intriguing, as (unlike the association between redness and ripeness) it does not reflect a naturally-occurring correlation. The typical flavour is actually predominantly made up from a mixture of esters from banana, cherry, and pineapple. The blue dye was originally introduced at a time of concern about the safety of the dark red that had been previously used to indicate a raspberry flavour (e.g., in cotton candy; [50, 153]). The flavour is now commonly used in sweetened beverages and dessert items, and because blue is so rarely encountered in other foods, the association to sweetness, and/or to the specific flavour, may be particularly strong. That said, a wide array of transparent blue drinks have come on to the market in recent years (see [153]), and new blue food dyes are popular, especially amongst the Instagram generation. Such learned associations are thus pretty arbitrary. They are, in other words, just like the ringtone that one happens to have installed on his or her mobile phone. Some years ago, Walker-Andrews [183] highlighted an important distinction between three classes of crossmodal association: arbitrary/natural, arbitrary/artificial, and what she labels typical crossmodal relations.

A separate question concerns how such crossmodal associations between colours and flavours are represented neurally. It is plausible that the brain builds up a range of priors as a result of statistical learning (e.g., [12, 38, 111]). Note how already at four months of age, babies have been shown to learn (i.e., internalize) the statistical correlation between the colour of the cup and the taste of the drink that happens to be contained within [104]. Similarly, with a relatively brief but repeated exposure paradigm, adults can learn a range of novel colour-taste associations [49]. Thus, a modelling approach with priors that are continually updated over the lifespan, to reflect the crossmodal statistics of the environment, would seem most appropriate. (Bear in mind here also that we can develop an aversion to a food after a single highly negative experience [13] and visual information can be an effective way to avoid aversive stimuli in the future. Intriguingly, though, it turns out that humans acquire an aversion to food/flavour whereas quails become averse to the colour of the food that made them ill [63, 192].)

According to a number of authors, a participant's age can influence the crossmodal influence of colour on taste/flavour perception (e.g., [83, 93]; see [135] for a review). It has been reported that younger children and older individuals tend to rely more heavily on visual cues when trying to identify the taste and/or flavour of food and drink than do adults. One suggested explanation for this finding is that the reduced reliability of gustatory/olfaction discrimination/categorization (as the chemical senses start their inevitable decline in old age) may result in a greater reliance on visual cues. Thinking in terms of Bayesian cue integration, it is worth highlighting how the optimal

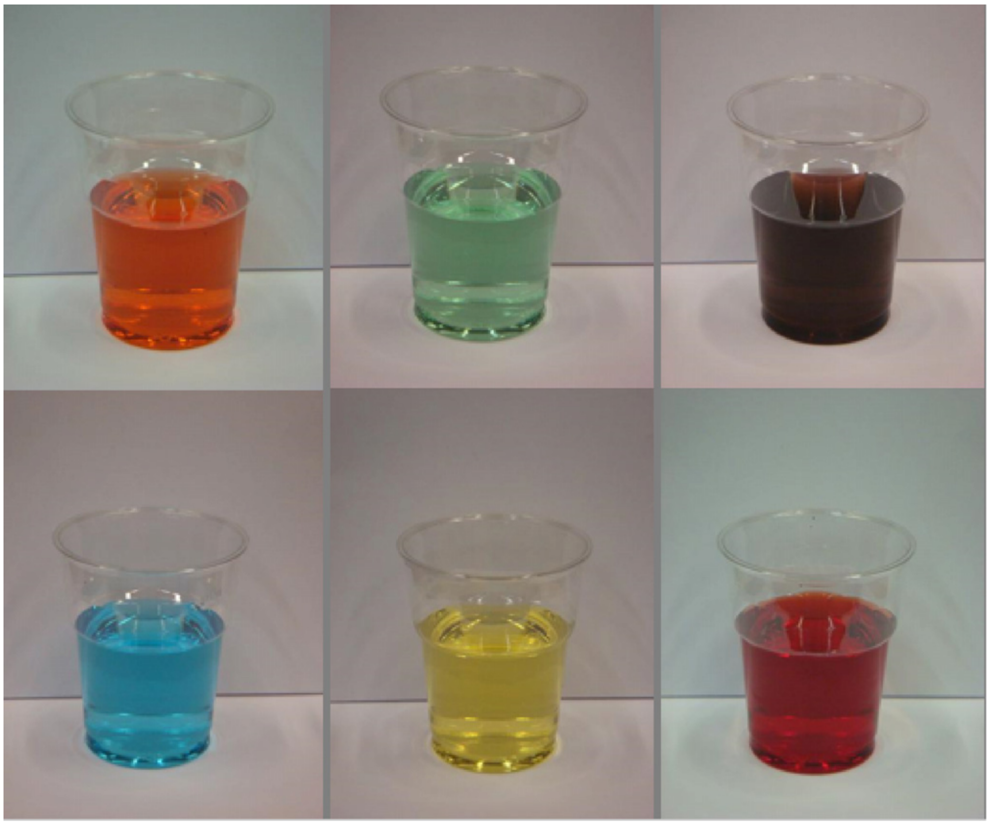

Figure 3. The six drinks shown to participants in the UK and Taiwan in a cross-cultural study of the flavour expectations elicited by colour [118]. The same images were later used in a large cross-cultural study [184].

multisensory integration of the spatial senses tends to come online at around 8-9 years of age [41].

2.2 *On the Relation Between Flavour Expectations and Flavour Perception*

In recent years, many researchers have increasingly wanted to distinguish between flavour expectations and flavour perception (e.g., [98, 135]; see also [1, 165]). The suggestion is that colour, not to mention other visual appearance cues, such as glossiness [77] and luminance distribution [177], just like orthonasal olfactory cues (on sniffing), help to set our flavour expectations (i.e., what we expect, or predict, a food to taste like prior to tasting it). These expectations may then bias flavour perception, the latter the result of the integration of retronasal olfactory, gustatory, and possibly also trigeminal/common chemical inputs (see [134], for a review). As such, one might be tempted to describe colour's influence over taste and flavour as crossmodal in nature rather than necessarily multisensory. That is, while colour cues may well influence the perceived taste/flavour via the taste/flavour expectations that they set, they are not, strictly-speaking, part of flavour perception (or the flavour object if you will) according to this framework.

Whenever we come across a food or beverage, we normally see it before we taste/consume it. The colour, and any other visual appearance properties, typically set an expectation about the food's likely flavour [118]. Providing that the flavour expectation is not too far removed from flavour perception, people typically report the expected flavour or, at the very least, assimilate the experienced flavour in the direction of the expected flavour. Importantly, however, should the discrepancy between the expected and experienced flavour be too great, it may lead to a negatively-valenced 'disconfirmation of expectation' response and contrast is likely to be the perceptual response instead [98, 112, 195]; cf. Shankar et al.'s 'degree of discrepancy' account [120]. That said, in certain specific contexts, such as the molecular or modernist restaurant, the surprise reaction to the disconfirmation of expectation can itself be highly desirable [97, 181]. However, by-and-large, consumers prefer it when their flavour expectations (set by visual cues) match up with their flavour perception. This situation is normally processed more fluently, and hence liked more, on average.

2.3 *Separating the Perceptual versus Decisional Effects of Colour on Flavour*

There has been debate amongst some of the more psychophysically-minded flavour scientists as to whether colour genuinely does (or can) change taste/flavour perception or rather whether it merely biases the response that the participants in laboratory studies are sometimes minded to give instead [48]. It would seem possible that the presence of colour in food could serve to focus a taster's attention and heighten their sensitivity to specific flavours—a perceptual impact in other words ([146]; see also [31]).

Alternatively, however, colour might instead predominantly influence people's criteria for responding—this would be considered a decisional effect. While much of colour's influence is evidenced in terms of bias, there does seem to be a genuinely perceptual effect as well, as, for example, demonstrated by Maga [69], who reported that the non-informative addition of colour modulated taste (i.e., gustatory) thresholds (see [158], for a review) as well as suprathreshold odour intensity [202]. There are multiple different crossmodal effects to be considered here though. Colour might influence taste/flavour thresholds and/or supratheshold intensity ratings. However, it might also influence taste or flavour identification responses and/or hedonic ratings (see [199]). Moreover, these various effects would seem, at least in principle, to be potentially independent. As highlighted by [158], the evidence that has been published thus far has provided more convincing support in certain of these cases than in others. So, for example, while the effects of adding colour on gustatory thresholds have been documented [69], we are not aware of any evidence suggesting that colour influences gustatory discrimination or identification performance, even though consumers have often been reported to confuse sour and bitter [47, 82].

3. MODELLING COLOUR-FLAVOUR INTERACTIONS

Given the rise of Bayesian causal inference as an explanatory framework for understanding multisensory integration in the spatial senses (namely vision, audition, and touch; [36]), it is natural to ask whether the same approach can perhaps be used to explain colour's influence over taste/flavour perception. (See also [72] on the use of information theory to try and model multisensory flavour perception.) According to the simplest version of such frameworks (e.g., Maximum Likelihood Estimation), multiple cues each have their own sensory reliabilities that then determine the relative weights of each source of information in the final percept/decision (e.g., [3, 37]). (Note that two of the assumptions underlying the MLE approach are that the noise in each of the sensory channels is independent and has a Gaussian distribution. However, Marks and colleagues have argued that, in the case of olfaction and gustation, the noise is pooled across the flavour senses [72].) Recent work [70] has demonstrated that this approach to modelling the combination of olfactory and gustatory cues can be successfully used to predict flavour choice (i.e., preference) in rats. In humans, meanwhile, those combinations of olfactory and gustatory cues that commonly co-occur in the foods that we consume have been shown to exhibit enhanced integration, including increased 'oral referral' [66, 67] (see also [140], for a review), as well as a greater crossmodal, or multisensory enhancement of smell by taste [17, 27]. However, there have not yet been any published papers that take a computational approach to colour's influence on flavour perception.

It is, however, important to stress that the crossmodal influences of orthonasal olfaction and vision on multisensory flavour perception would appear to be qualitatively different [7]. In part, this may be because of the somewhat confusing interaction/overlap between orthonasal and retronasal olfaction [106, 193]. While strictly-speaking orthonasal olfactory cues help to set flavour expectations (i.e., rather than being part of flavour experience), there is evidence that such cues are nevertheless sometimes integrated into multisensory flavour experiences (see [150], for a review).

By including priors, Bayesian models can accommodate the role of expectations. For example, when the brain processes information from different senses, assumptions about whether the sources arise from a common cause can be modelled as a prior [59]. When information from, say, sound and vision seem to be plausibly related (e.g., one hears a voice at the same time that one sees a moving mouth), the brain may be more likely to integrate that information than when they seem unlikely to be related (e.g., one hears an alarm clock while viewing a moving mouth). Spatiotemporal coincidence can also be treated as a prior, at least when combining cues/information from the spatial senses (e.g., [23, 79]; though see also [119]). According to Bayesian models, the likelihood that different sensory inputs (such as a given colour and a particular taste/flavour) belong together can be represented as 'coupling priors', sometimes referred to as a 'prior of common cause' (e.g., [35, 110, 117]). These priors are combined with the likelihoods of each input. As such, the Bayesian approach provides one means of formalizing different degrees of certainty regarding the unity of two or more unisensory inputs as a continuous (rather than as a discrete) variable (e.g., [59]). For the spatial domain, this is relatively straightforward to imagine—the individual sensory inputs for visual and auditory locations would each have their own uncertainty, and the coupling prior would represent the probability that the two inputs shared a common cause. If the uncertainties in the individual estimates are relatively high, and the coupling prior is strong, people are likely to perceive a unified audiovisual signal, even if the two signals come from different locations (as with the ventriloquism effect); however, if the uncertainties are smaller, then a spatial discrepancy can become more perceptible (consistent with the 'degree of discrepancy' account [120]). So it is the relative uncertainties in the coupling prior and the individual sensory likelihoods that determine whether integration or segregation is more likely to occur.

So, how might one conceptualize coupling priors in the case of multisensory flavour perception [23]? Given the large diversity in flavour experiences across both culture and over time [50], it would seem unlikely that people have evolved highly specific innate associations between particular colours and tastes/flavours. The one possible exception here might relate to the tendency to match more saturated colours with a more intense taste/flavour; one might think of this as an example of an innate correspondence based on intensity matching [133, 169]. However, it is worth noting that people may also have internalized a statistical regularity that is perhaps also present in manufactured food products (i.e., foods with a more intense taste/flavour are often given a more saturated colour in the marketplace), thus making the origins of any such intensity/saturation mapping hard to determine definitively.

3.1 *Challenges Associated with Trying to Model Flavour*

Several challenges arise when one attempts to model multisensory flavour perception, the first of which is one of dimensionality. For, in contrast to visual information, which can be characterized in terms of properties of light at different spatial locations, the dimensionality of flavour (or even just aroma, given that 75–95% of what we think we taste we really smell; see [138], for a review) is far more complicated, likely requiring a high-dimensional space. For example, the relationships between the flavour profiles of strawberry, coffee, onion, and orange are far more complex to characterize than the relationships between different colour patches in an image. While it is possible to array a selection of flavourful stimuli within a similarity space, it is rarely clear what the dimensions describing (or underpinning) that space are, and how generalizable they might be to the assessment of other combinations of flavourful stimuli. For example, one study of odours found that perceived similarity between odours could be predicted using a model with 21 physicochemical features [103]. By contrast, in a study that asked participants to rate the similarity of all 55 pairs of 11 spices, the results revealed that all the stimuli were arranged along a single 'pleasantness' dimension [58].

However, as highlighted by another early study [14], similarity judgments for herbs and spices (and basic tastants; e.g., sugar) are markedly influenced by a consumer's prior experience; for example, some groups find nutmeg to be sweet whereas for others it has a more savoury association (see also [39]). It is perhaps also worth noting here that these similarity judgments are typically based on orthonasal olfactory judgments, and it is by no means always certain that the same ratings would be obtained for retronasal olfaction. Note that it is retronasal olfaction that is constitutively involved in flavour perception whereas orthonasal olfaction is rather associated with setting our flavour expectations. Rozin has highlighted that, occasionally, the pleasantness of aromas/flavour experienced orthonasally versus retronasally may be quite different. Rozin gives the example of fresh ground coffee that may smell wonderful orthonasally, while being disappointing when experienced retronasally. Meanwhile, a ripe Epoissé cheese smells awful orthonasally while at the same time delivering what many consider a divine retronasal flavour experience [106].

The foods that we consume typically consist of a mixture of different ingredients. However, we typically do not experience the combination simply as an average of its parts. For example, pad thai noodles include sweet, sour, bitter, salty, and umami elements – and those are just the basic tastes. It is often made with fish sauce, which has an odour that some people find unpleasant. How, then, to model such a complex flavour profile? A similar problem occurs when we consider a physically (and also perceptually) complex single flavour such as coffee or wine, which may consist of anywhere between 600 and 1,000 different compounds (see [163] for a review).

The majority of studies of audiovisual integration require participants to integrate information having only small discrepancies in time, space, or linguistic characteristics in the case of audiovisual speech perception (so that the unity assumption is not violated) [23]. This helps to make the computational modelling relatively straightforward. However, consider here only how the colour yellow could be associated with cheese, butter, pineapple, peppers, or lemons. As such, if one were to try to model the integration of the colour expectations with gustatory information, one would first need to establish the appropriate association/dimensions *a priori*. Maier and Elliott [70] took an interesting approach by using flavour choice as their behavioural response measure; preferences may be one way to "standardise" across the senses. However, their study was conducted with rats and relied upon conditioning a relationship between a specific odour and caloric density. In humans, the preference space is presumably much more complex.

Another key consideration is that while colour cues may be correlated with specific tastes/flavours as a result of statistical learning [10, 35], the colour signal does not provide an estimate of the same physical stimulus/dimension (namely taste, flavour, or perhaps the energy density/fat content of a food). Given that the colour is merely correlated with the taste/flavour, one might want to question whether it even makes sense to talk of the precision or accuracy of colour cues. As C. S. Peirce put it 150 years ago: "Sight by itself informs us only of colours and forms [and that] No one can pretend that the images of sight are determinate in reference to taste" [92]. An additional factor to consider when modelling responses to flavour is categorical perception. Human perception of both colour and odour can be considered as categorical [51], and thus any model of flavour perception would need to account for this (see also [125]). However, given current uncertainties about the appropriate dimensions of flavour (as described above), this task would likely be challenging. And while there have undoubtedly been some recent successes in the multisensory modelling of audiovisual speech perception [11, 68, 80], it is worth noting that the phonemic structure of speech is currently much better understood than the structure of flavour. For instance, just think about how the difference between a /ba/ and a /ga/ sound can be characterized using a spectrogram of the speech content, whereas the difference between strawberry and cherry is more complex to capture.

Note here only how the different senses involved in multisensory flavour perception tend to provide information that is qualitatively rather than quantitatively different, further complicating the attempt to model the combination of such information. By contrast, much of the modelling work on multisensory integration has involved different sensory estimates of the same "amodal" stimulus property (e.g., [65]; though see [157]), such as the seen and felt height of a bar [37, 41], or the position of the stimulus/event in audiovisual studies of the ventriloquism illusion [3].

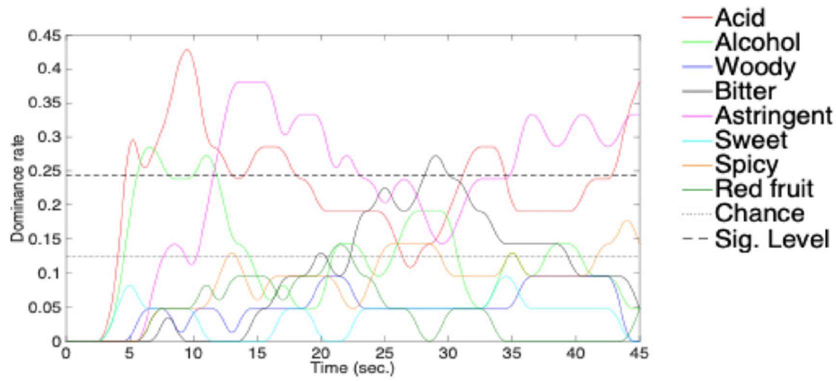

Figure 4. A mouthful of Manos Negras Pinot Noir 2014 held in the mouth for a period of 45 seconds. Note that the horizontal dashed lines indicate chance level responses (given the eight possible descriptions) and a significant response across the group of participants whenever the time series exceeds a dominance level of 0.25. From [185].

Having elucidated the problems for modelling multisensory flavour perception, one can ask what strategies are, or could potentially be, used to acquire the relevant data. The ideal dataset would involve assessing taste-flavour expectations based on visual cues, taste-flavour ratings in the absence of vision, as well as combined ratings. It might also be desirable to assess people's confidence in their own judgments. Varying the reliability/uncertainty associated with judgments in each modality when assessed in isolation would also be important. While psychophysical data is currently the most relevant, one could potentially imagine, in the future, the relevance of neurophysiological studies in the animal model (cf. [105]).

Tastes often mask one another [16], and taste/odour masking is also a commonplace occurrence [19, 172]. Tastes can also enhance our ability to perceive aroma [28]. That is, in multisensory flavour perception there is simply no one-to-one mapping between the physical concentration of chemical stimuli and the perceived taste or flavour. Consider here only how within a certain range adding salt to tonic water actually makes it taste sweeter due to release from masking from the bitter taste. As such, it may be more relevant to talk about accuracy in terms of perception rather than the physical stimulus itself. Complicating matters further, people also sometimes confuse bitter and sour [47], not to mention the ubiquitous confusion that we all experience between smell and taste [106, 156]. Although the physical properties and sensory processing pathways are quite distinct (and increasingly well elucidated), people experience flavour as a result of the combination of both retronasal olfactory and taste/gustatory inputs. What is more, statistical learning can rapidly change the associations between these senses, as well as the sensory properties of the component stimuli (e.g., [101, 171, 196]; though see also [39]). There is also extensive evidence that (especially novel) odorants soon come to take on the gustatory properties of the tastes with which they are normally paired [152, 170]. So, for example, many people consider vanilla to smell 'sweet', because of their exposure in ice cream and cola, despite the fact that vanilla pods actually taste very bitter.

Finally, our experience of the flavour of many food and drink products typically unfolds over time [164]. For instance, the Temporal Dominance of Sensations (TDS) graph in Figure 4 from [185] shows the different aromas/flavours that come to the fore while holding wine in the mouth for 45 s. In this TDS study (see also [94]), the participants were invited to rate the different tastes/flavours that were salient in their perception of the flavour of the wine at each moment. As the graph helps to make clear, the multisensory flavour of the wine (which can be considered as having a particularly complex flavour profile; see [163]) changes dynamically.

3.2 *The Network Model Approach*

Given all of the challenges of a parametric approach, an alternate strategy might be to create a network model to represent the possible flavour space in terms of different concepts (see [54] for a general overview of such models). These models have generally been used in the language domain, such as to represent a semantic network that relates words based on similarity in meanings. Hutchison [54] uses the example of the concept of a cherry to illustrate how such networks could work. A network could be holistic, with a dedicated node in the network for each concept. Through repeated experience with red cherries, the nodes for the individual concepts of red and cherry could become connected to each other. Many holistic semantic models posit automatic spreading activation—that is, when one concept is activated, activation spreads to associated concepts. If one were to apply such a model to flavour, one could imagine that seeing a coloured food could lead to activation of multiple potential flavours. The colour green would presumably be more strongly connected to lime than to caramel, with lemon likely intermediate in strength (except in countries like Colombia where lemons are green). A process of spreading activation could occur as one sees, smells, and tastes a food or beverage (cf. [90]). For relatively simple experiments that require participants to name one or more flavours associated with a colour, participants could use a strategy of naming the concepts with the strongest activation. In a complex situation, such as tasting wine, one might imagine this activation changing over time with oral and retronasal processing, and perhaps activation of specific concepts even enhancing attention to different components of the wine.

An alternate approach is to use a distributed network model. Here, concepts would not be represented by discrete nodes, but instead by the activation across nodes within the network. Individual nodes might be specific features, with their weighed combinations signalling specific concepts. In Hutchison's [54] cherry example, nodes might exist for features such as roundness, edibility, and juiciness. No one specific node would exist specific to cherries; instead, they would be specified (and differentiable for other related concepts) based across a large number of features. Considering how to apply this approach to colour and flavour, redness might be one of the features that makes up part of the distributed ensemble of nodes that are active when one sees or thinks of a cherry. In the case of an ambiguous flavour, then, the presence of colour could lead the overall activation pattern to more closely favour particular interpretations.

Such approaches have potential, but it is worth highlighting that they would require large datasets to implement and test properly. Datasets exist for words; for instance, the English Lexical Project collected data for 40,481 words and 40,481 nonwords to build their dataset [8], and the semantic priming project used data from 768 participants for 1661 target words [55]. However, as described below, there are substantial practical challenges involved in collecting data when using flavour stimuli.

4. THE COGNITIVE NEUROSCIENCE OF COLOUR-FLAVOUR ASSOCIATIONS/INTERACTIONS

Because cognitive neuroscience methods typically require participants to remain quite still, there are particular challenges associated with attempting to conduct ecologically-valid experiments with food. For example, in functional magnetic resonance imaging (fMRI), typical flavour stimuli consist of liquids, to avoid chewing and minimize swallowing, presented with controlled timing and temperature [18], often washed down with a squirt of artificial saliva! All the practical challenges described above apply, with the addition of confined movement for both fMRI and electro-encephalography (EEG), and a very restricted space for the participant to lie in the fMRI machine itself.

4.1 *Practical Challenges*

There are empirical challenges hindering the ability to computationally model multisensory flavour perception. For instance, in order to differentiate among possible models of multisensory integration, extensive empirical data is necessary. While syllables can be presented hundreds, or even thousands, of times in an experimental session to collect sufficient data, this is simply much more difficult to achieve in the case of flavour stimuli. Note here also how participants adapt rapidly to olfactory or gustatory stimulation, and thus require much longer intervals and/or neutralizing stimuli to be presented between trials (see also [91, 178]). Flavour stimuli are also more challenging to control precisely; for instance, asking participants to chew for a specified interval will result in higher variability than presenting video stimuli that can simply be repeated and counterbalanced across an experimental session. In other words, one might consider flavour perception as a much more active, and hence harder to control, process than is typically the case for audiovisual perception, say ([26, 108]; see also [6]). Nevertheless, despite these obstacles, there has been some successful cognitive neuroscience research on how colour influences taste/flavour/odour perception [53, 85, 194].

One approach is to consider colour as a top-down influence that biases perception by creating expectations but functions in a similar way to other cognitive influences such as labels or attentional factors [126]. Research on colour-odour interactions involving consistent versus inconsistent combinations of unisensory stimuli suggests that the orbitofrontal cortex (OFC) and insular cortex are sensitive to congruency [85]; both of these areas are also considered crucial to the brain's flavour network [85, 126, 128, 129]. For instance, Skrandies and Reuther (2008) highlighted differing patterns of electrical activity in the human brain as a function of the matching/mismatching of taste, odour, and colour [167]. Given recent advances in technology and data analysis, we are hopeful that more naturalistic cognitive neuroscience research involving more realistic flavour experiences will soon be possible. For example, mobile EEG is now at the point where participants can move during data acquisition [42]. However, even with all of these technological advances, it should be remembered that neuroscience methods typically require data averaging to minimize neural noise.

Finally, it is also worth stressing that many of the most intriguing flavour experiences cannot be replicated: Think only here of the pleasant surprise response elicited in many diners on first being served the beetroot and orange jelly dish at The Fat Duck restaurant. Made with blood red oranges and golden beetroots, the normal colour-flavour mapping has been cleverly reversed [141]. Present day technologies and computational analyses require averaging over multiple trials, but some of the most compelling flavour phenomena are one-shot in nature; this gap between experimental and true (i.e., ecologically-valid) eating and drinking experiences is likely to remain a barrier to advances in this area for years to come.

5. EMERGING DIRECTIONS IN COLOUR-FLAVOUR RESEARCH

5.1 *When Colour's Meaning Becomes Symbolic*

In some cases, the colour of food and drink can take on a more symbolic, or mediated, role (or meaning). For example, when viewing black and white photos of food, people do not expect the food itself to taste of the flavours we normally associate with those foods that are actually black and white, such as olives and mozzarella cheese, for example [160]; a black and white photo of a bakery case full of cakes versus a butchers' case of meats would still lead to very different flavour expectations, as the viewer imagines the colours that those foods would normally have. However, if one were to experience a black and white meal in person, this might be associated with funerary symbolism, or as deliberate absence of colour [143, 154]. Branded colour also feels like it takes on a distinct meaning (think here only of bright Pepto-Bismol pink; [190]). It is an open question whether it is the red or Coca-Cola branding that first comes to mind, or brown colour, when tasting cola. There is perhaps something of a contrast with our association with fruits. Notice how it is the colour of the flesh, not the skin or peel, that we tend to associate with the flavour. And consider how the smell or taste of ripe tomatoes is associated with a deep-red colour, despite the fact that the majority of the aroma actually comes from the stalk and leaves, which are actually green (see also [84]).

In the current era of ubiquitous social media, the colour of food and drink are often playfully used to draw people's attention to a specific dish or food experience. Hence, rather than colour simply acting as a conventional signifier of a specific taste/flavour that may be associated with a given food, it is instead used to capture a viewer's visual attention precisely because of a violation of expectations, and/or because a particular colour (e.g., blue), or array of colours (as in rainbow-coloured dishes) are unlikely to be associated in the viewer's mind with any particular taste/flavour profile. In recent years, rainbow bagels have gone viral and Starbucks briefly offered a unicorn Frappuccino. Even black foods enjoyed a moment in the spotlight, with both McDonalds and Burger King offering black hamburgers in Japan (the Burger King version even included black cheese), and black ice cream also having become something of a food trend [154]. Food and drinks that change colour have also become increasingly fashionable too [147]. In contrast to the blue raspberry flavour described above, which has led to the development of a particular colour-flavour association, purveyors of rainbow and black foods are promising a novel experience, where the colour itself is not actually related to a specific flavour, but instead to a more experimental, or whimsical, consumption experience.

5.2 *Environmental, Augmented Reality, and Virtual Reality Colours*

There is an emerging literature on AR and VR tasting experiences [22, 52, 159, 177, 187]. However, one of the first questions to address in this space is whether the knowledge that the colours that we see are virtual, or that the drink has been digitally augmented, matters. Apparently not—or at least real and virtual colours have so far been shown to exert much the same effect on taste/flavour rating [4]. While this might appear surprising, given that the participants in these studies are normally aware that their visual experience has been manipulated in some way (and so should, perhaps, not be trusted), it turns out that simply telling people that they should ignore the actual colour of drinks that they have to evaluate does not seem to preclude colour from impacting the tasting experience [89, 197, 198].

There is also mounting evidence to suggest that the colour of cups [21], cutlery [43], plates [2, 96], packaging [161], advertising [186], and even the colour of the environment itself [22, 81, 162] (see [144], for a review) can influence flavour perception (and possibly also a consumer's appetite [25]). Why should things taste sweeter in a pink environment [22]? Is it simply that colour automatically sets expectations regardless of whether it happens to be in the actually tasted food or beverage? Should this be considered a failure of binding? Or might it instead be considered an example of 'sensation transference' [24]? The evidence suggests that colour automatically primes a variety of associated concepts [24]. However, one might consider whether having participants explicitly associate a taste with a colour at the start of a study (e.g., as in [21, 76]), might not somehow prime them to a colour-taste mapping that they might not otherwise consider. It seems like the effect of ambient colour from a coloured environment can sometimes be as large as or even in some cases larger than the effect of colour in food itself (though see also [201]).

Food and drink colour might also prime notions of artificiality, though as Hisano [50] has recently highlighted, even the colour of everyday foods such as butter, oranges, and bananas has been constrained, prescribed, and standardized over the centuries. Thus, it's possible that the colours that have been considered appropriate for specific food items are, or once were, mediated by emotional responses but have, over time, become statistical correspondences as well. For instance, the use of blue for raspberry may initially have been novel and hence attention-capturing (just as rainbow bagels and unicorn-coloured drinks might be today), as well providing a visually-distinctive means of differentiating from other flavours, such as cherry; today, the pairing is common enough that many people likely learn the association through experience.

One final point to note here is that the majority of laboratory studies of food colouring involve artificial/synthetic flavours. They can sometimes lead to different colour matches than those of the actual natural products themselves. So, for instance, people tend to match the smell of strawberry to a pinkish colour whereas the ripe fruit are themselves typically a much richer red colour [30]. Increasingly, it is now also becoming possible to modify the colour of food dynamically using food chemistry or clever lighting manipulations (see [147], for a review), as illustrated by the recently-discovered neon fruit illusion [45]. What is more, the effects very often appear to be indistinguishable in terms of their magnitude and automaticity from when the colour happens to be in the flavourful stimulus itself [137, 158].

6. CONCLUSIONS

As this review of the literature has hopefully made clear, colour affects taste/flavour perception in a multitude of ways. There is converging evidence that the colour of food and drink helps set taste/flavour expectations and that these expectations, which would appear to be generated in a fairly automatic manner prior to tasting, bias the subsequent multisensory flavour experience. There is substantial empirical evidence that colours are associated with specific flavours, and that these associations are mostly learned as a result of the internalization of the statistics of the environment. What is more, the research shows that there are perceptual consequences of these crossmodal associations, provided at least that the degree of discrepancy between the flavour expectations set by colour does not differ too much from the actual flavour.

At a more abstract level, we do not yet have the right kinds of data, nor do we understand the dimensionality of flavour space. However, as both modelling and neuroscientific methodologies advance, we are optimistic about the insights to be made in coming years. It is possible that machine-learning and the rapidly growing field of computational gastronomy may also deliver some relevant insights concerning the way in which flavour space should be conceptualized (see [151]). Given the success of Bayesian causal inference in other areas of multisensory perception research, it is to be hoped that the same approach can be fruitfully applied to explain/predict colour's influence over multisensory flavour perception. As highlighted earlier, this will likely require the collection of extensive psychophysical datasets, involving unimodal and multisensory judgments of expected/actual taste/flavour, preferably with the unimodal judgments obtained at different levels of reliability. An individual's subjective degree of confidence in the meaning of colour may also provide useful information (cf. [102]).

Perhaps unsurprisingly, despite all the research on colour's influence over taste and flavour that has been conducted over the last 80 years or so (e.g., since Moir's early study [74]), there are still a number of questions that we still do not have a satisfactory answer to. These include the following: Is the crossmodal influence of colour over taste mediated by flavour? What, exactly, is the relation between the strength and ambiguity of colour-flavour mappings? Under what conditions does product extrinsic (and/or intrinsic) colour affect taste/flavour perception? Is it possible to model colour's influence over multisensory flavour experience in terms of Bayesian causal inference? Answering such questions will likely help in food product development (and experiential marketing) in the years ahead (e.g., [2, 15, 73]).

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