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Does Food Color Influence Taste and Flavor Perception in Humans?

Charles Spence · Carmel A. Levitan · Maya U. Shankar · Massimiliano Zampini

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Abstract In this paper, we review the empirical literature concerning the important question of whether or not food color influences taste and flavor perception in humans. Although a superficial reading of the literature on this topic would appear to give a somewhat mixed answer, we argue that this is, at least in part, due to the fact that many researchers have failed to distinguish between two qualitatively distinct research questions. The first concerns the role that food coloring plays in the perception of the *intensity* of a particular flavor (e.g., strawberry, banana, etc.) or taste attribute (e.g., sweetness, saltiness, etc.). The second concerns the role that food coloring plays in the perception of flavor *identity*. The empirical evidence regarding the first question is currently rather ambiguous. While some researchers have reported a significant crossmodal effect of changing the intensity of a food or drink's coloring on people's judgments of taste or flavor intensity, many others have failed to demonstrate any such effect. By contrast, the research findings concerning the second question clearly support the view that people's judgments of flavor identity are often affected by the changing of a food or drink's color (be it appropriate, inappropriate, or absent). We discuss the possible mechanisms underlying these crossmodal effects and suggest some of the key directions for future research in order to move our understanding in this area forward.

Keywords Flavor · Taste · Color · Perception · Crossmodal · Multisensory · Expectancy · Attention

C. Spence · M. U. Shankar
Department of Experimental Psychology, University of Oxford, Oxford, UK

C. A. Levitan
Cognitive Science Program, Occidental College, 1600 Campus Road, Los Angeles, CA 90041, USA

M. Zampini
Center for Mind/Brain Sciences & Department of Cognitive Sciences and Education, University of Trento, Rovereto (TN), Italy

C. Spence (✉)
Crossmodal Research Laboratory, Department of Experimental Psychology, University of Oxford, Oxford OX1 3UD, UK
e-mail: charles.spence@psy.ox.ac.uk

Introduction

Does food coloring influence taste and flavor perception in humans? Although researchers have been investigating this important (both on a theoretical and practical level) question for more than 70 years now (see Duncker 1939; Masurovsky 1939; Moir 1936 for early research), an unequivocal answer to the question has not, as yet, been reached. That, at least, would seem to be the conclusion drawn by the majority of researchers in the field. Take, for example, Lavin and Lawless's (1998, p. 284) claim that "The literature on the effects of color on taste and flavor judgments is consistent in its inconsistency" or Koch and Koch's (2003, p. 240) statement that "In fact, it may be that color has nothing to do with the taste of food or drink." Meanwhile, Bayarri et al. (2001, p. 399) have also suggested that "…the possible influence of color on flavor perception is under discussion and no clear conclusions have been attained yet." In the present article, we argue that one important reason why our understanding of the nature of any crossmodal effects of food coloring on taste and flavor perception in humans has progressed so slowly relates to the fact that many researchers have failed to distinguish between the evidence pertinent to evaluating two relatively independent research questions: (1) Does the presence versus absence, or change in the intensity, of the color present in a food or drink influence people's perception of the *intensity* of a particular flavor (e.g., banana, strawberry, etc.) or taste (such as sweetness, sourness, etc.)? (2) Does food coloring influence the correct *identification of a food or drink's flavor?*

The evidence concerning the first question is indeed rather mixed (Auvray and Spence 2008; Stevenson 2009; Zampini et al. 2007), with some researchers observing a significant effect of changing the intensity of the coloring added to a food on people's judgments of flavor and/or taste *intensity* (e.g., Johnson and Clydesdale 1982; Johnson et al. 1982, 1983; Roth et al. 1988), while many others have failed to demonstrate any such effect (e.g., Alley and Alley 1998; Frank et al. 1989; see Table 1). By contrast, the published evidence unequivocally supports an affirmative answer to the second question, with people's judgments of a flavor's *identity* often being reliably affected by a food's color, be it appropriate, inappropriate, or absent. Note here that we are not aware of any research having been conducted assessing the effect of color on the identification of basic tastes (e.g., when solutions containing an odorless tastant such as sugar or salt are sampled). Below, we review the evidence relating to these two questions. We discuss several of the possible mechanisms that may underlie these crossmodal effects on taste and flavor identification, such as cognitive expectancy, bottom-up multisensory integration, and attention.

Which Senses Contribute to the Perception of Flavor?

Before we proceed, however, it is important to note that gustatory, olfactory, and oral–somatosensory cues (in contrast to visual and auditory cues) all contribute directly to flavor perception. In fact, the International Standards Organization (ISO 5492 1992) has defined flavor as a "complex combination of the olfactory, gustatory and trigeminal sensations perceived during tasting. The flavor may be influenced by tactile, thermal, painful and/or kinaesthetic effects" (see Delwiche 2004, p. 137; see also ISO 5492 2008). Visual and auditory cues may modify a food's flavor, but they are not, at least according to the ISO definition, intrinsic to it (though see also Auvray and Spence 2008; Stevenson 2009 for alternative views). Visual cues, such as a food's color, may then modify the perception of a food's flavor by influencing the gustatory qualities of the food, by influencing the olfactory attributes of the food (as perceived orthonasally and/or retronasally; Koza et al. 2005), by influencing the oral–somatosensory qualities of the food, and/or by influencing the overall multisensory flavor percept (or Gestalt; see Fig. 1). In this article, we review the evidence regarding color's effect on taste and flavor. We also discuss the evidence regarding color's influence on olfactory judgments where relevant.[1]

Does Food Color Influence Perceived Taste or Flavor Intensity?

The evidence pertaining to the question of whether food coloring influences people's perception (or ratings) of taste or flavor *intensity* is currently rather ambiguous: that is, while a number of studies have demonstrated a significant effect of increasing the level of food coloring on people's ratings of taste or flavor intensity across a range of different drinks (Hyman 1983; Johnson and Clydesdale 1982; Johnson et al. 1982, 1983; Kostyla 1978; Romeu and De Vicente 1968; Roth et al. 1988), many other studies have either failed to demonstrate any such crossmodal effect (e.g., Alley and Alley 1998; Chan and Kane-Martinelli 1997; Frank et al. 1989; Gifford and Clydesdale 1986; Gifford et al. 1987), or else have demonstrated complex (and/or unexpected) interactions that have proved rather more difficult to interpret (e.g., Christensen 1985; DuBose et al. 1980, experiment 1; Fletcher et al. 1991; Lavin and Lawless 1998; McCullough et al. 1978; Pangborn 1960; Strugnell 1997; Zampini et al. 2007; experiment 2).[2] Given that the evidence regarding color's influence on taste intensity would appear to be rather more ambiguous than its effect on flavor intensity, the evidence pertaining to each of these is dealt with separately in the following sections.

Does food color influence taste intensity? One of the classic studies to investigate color's influence on taste sensitivity was conducted by Maga (1974). He investigated the effects of coloring an aqueous solution red, green, or

[1] It should be noted that the near absence of research means that, as yet, there is nothing much to say about vision's influence, if any, on the oral–somatosensory attributes of flavor (see Christensen 1983; de Wijk et al. 2004; Frost and Janhoj 2007 for exceptions; see Verhagen and Engelen 2006 for a review).

[2] Over the years, researchers have looked at color's role in influencing people's perception of the taste and flavor of many different foods, including jellies (Moir 1936), cake (DuBose et al. 1980; Moir 1936; Tom et al. 1987), chocolate (Duncker 1939; Levitan et al. 2008; Shankar et al. 2009), syrups (Kanig 1955), sherbets (Hall 1958), wine gums (Teerling 1992), and yogurt (Norton and Johnson 1987). However, more recently, the majority of the research has tended to use various different drinks, beverages, and solutions as the stimuli of choice. Most likely, this research focus on colored drinks (be they carbonated or uncarbonated) reflects both the ease of stimulus control and creation that such experimental materials afford and also the fact that color provides one of the few distinctive non-olfactory features of such stimuli (see Christensen 1985; Oram et al. 1995). Given this bias in the literature, we have also chosen to focus our review primarily on those studies that have investigated the effect of color on taste and flavor perception in various solutions, drinks, and beverages.

Table 1 Summary of the studies that have been published to date that have investigated the effect of varying the presence vs. absence, the appropriateness/inappropriateness, or the intensity, of the color added to a solution on participants' taste and/or flavor (Fl) intensity ratings. The table highlights the fact that the majority of research in this area has focused on the influence of color on sweetness perception. The table also highlights the inconsistency in the pattern of results that has been reported to date across the various studies that have been reported

Study	Tastant	Flavor	Result
Pangborn (1960)	Sw, So		Sig
Pangborn et al. (1963)	Sw		Sig
Romeu and De Vicente (1968)		Fl	Sig
Maga (1974)	Sw, Sa, So, Bi		Sig
Kostyla (1978)	Sw, So	Fl	Sig
McCullough et al. (1978)	Sw		Complex
DuBose et al. (1980)		Fl	Complex
Johnson and Clydesdale (1982)	Sw		Sig
Johnson et al. (1982)	Sw		Sig
Hyman (1983)		Fl	Sig
Johnson et al. (1983)	Sw		Sig
Gifford and Clydesdale (1986)	Sa		n.s.
Gifford et al. (1987)	Sa		n.s.
Roth et al. (1988)	Sw		Sig
Frank et al. (1989)	Sw		n.s.
Fletcher et al. (1991)	Sw		Complex
Philipsen et al. (1995)	Sw		Sig
Chan and Kane-Martinelli (1997)	Sa		n.s.
Strugnell (1997)	Sw		Sig
Alley and Alley (1998)	Sw		n.s.
Lavin and Lawless (1998)	Sw		Complex
Bayarri et al. (2001)	Sw	Fl	Complex
Zampini et al. (2007)		Fl	Complex
Zampini et al. (2008)	Sw, So	Fl	Complex

Sw sweet, *Sa* salt, *So* sour, *Sig* significant result, *n.s.* non-significant result, *Complex* typically a mixture of significant and non-significant results

yellow on perceptual thresholds for four of the basic tastes (salty, sour, sweet, and bitter). Note that each of the basic tastes was tested in a separate part of the experiment, meaning that the participants were presumably never uncertain with regard to the identity of the tastant whose presence they were trying to detect. In many cases, Maga observed that the concentration of the tastant had to be increased in order for his participants to be able to detect its presence in the colored (as compared to the uncolored) solutions. So, for example, the addition of green coloring to a sweet solution significantly increased taste sensitivity, while yellow color decreased taste sensitivity (see Table 2). Interestingly, red coloring had no significant effect on sensitivity to sweet taste. With respect to sour taste sensitivity, both the yellow and green coloring of solutions decreased participants' sensitivity, with red coloring again having no effect. Coloring a clear solution red decreased bitter taste sensitivity, while the addition of yellow and green coloring had no such effect. Finally, adding color had no effect on taste detection thresholds for salt solutions.

Johnson and Clydesdale (1982), in an oft-cited study, demonstrated an effect of food coloring on taste perception in sweetened solutions (that sometimes contained a cherry flavoring). The participants in their study had to perform both a threshold task and a magnitude estimation task. In the threshold task, Johnson and Clydesdale found that on average, when odorless solutions were colored red, participants could more easily detect the presence of sucrose than when they were uncolored (cf. Maga 1974), though the intensity of the color did not have a significant effect on their performance. In the magnitude estimation task, however, Johnson and Clydesdale found that changing the level of food coloring had a significant effect on participants' perception of the sweetness of both odorless and cherry-flavored solutions, with the darker-colored solutions being rated as 2–10% sweeter than the lighter-colored

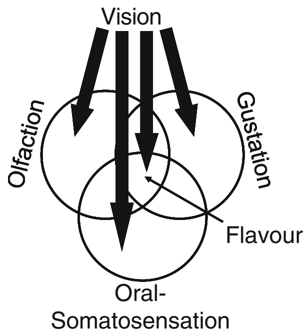

Fig. 1 This figure highlights the multiple ways in which visual cues might influence flavor perception. Visual cues (such as the color of a beverage) may exert a crossmodal influence on olfaction, gustation, and/or on oral somatosensation. Such crossmodal effects, should they exist, might then have a carryover effect on the experienced flavor percept once the various unisensory cues have been integrated. Alternatively, however, visual information might influence flavor perception only once the olfactory, gustatory, and/or oral–somatosensory cues have been integrated into a multisensory flavor percept (so, for example, if you bite into a filled chocolate, then look to see what color the filling of the chocolate has, then color may well influence the integrated flavor percept). Complicating matters still further, the nature of the crossmodal influence of visual cues on flavor perception may well vary with the task at hand. That is, different results may be observed as a function of whether participants are asked to report on the pleasantness or intensity of a flavor versus having to identify or discriminate the flavor. There is robust psychophysical evidence that visual (color) cues can modulate people's perception of the identity and intensity of both orthonasally and retronasally presented odors (e.g., Blackwell 1995; Davis 1981; Engen 1972; Morrot et al. 2001; Zellner et al. 1991; Zellner and Kautz 1990; Zellner and Whitten 1999). There is also convincing psychophysical evidence that visual (color) cues can influence people's perception of the intensity of the basic tastants when presented in odorless solutions (Johnson and Clydesdale 1982; Maga 1974). Interestingly, however, we are aware of no research that has directly addressed the question of whether color cues can influence a participant's ability to discriminate (and/or identify) the identity of basic tastants when presented in solution. To date, there is only very limited research detailing any visual contributions to the oral–somatosensory attributes of food. Evidence demonstrating the robust influence of visual cues on flavor identification is discussed in the text, as is the rather more mixed evidence concerning the influence of visual (color) cues on perceived taste and flavor intensity

reference solutions despite the fact that the actual concentration of sucrose was 1% lower. In further studies, Johnson and his colleagues went on to use the same magnitude estimation procedure in order to show that sweetness ratings for both cherry- (Johnson et al. 1982) and strawberry-flavored drinks (Johnson et al. 1983) increased by 2–13% when the intensity of the cherry red coloring was increased. Over the years, several further studies have also documented a significant effect of the addition of (specifically) *red* food coloring on the perception of *sweetness* (e.g., see Kostyla 1978; Pangborn 1960; Strugnell 1997).

Color cues have also been reported to influence participants' ratings of sourness/tartness (e.g., Kostyla 1978; Pangborn 1960). By contrast, the null result of color on the detection threshold for the presence of salt in aqueous solutions reported by Maga (1974) has been extended in several other well-controlled laboratory studies in which coloring was added to more ecologically valid food substrates, such as chicken broth (see Chan and Kane-Martinelli 1997; Gifford and Clydesdale 1986; Gifford et al. 1987). In order to try and explain this seemingly inconsistent effect of the addition of color on salt and sweetness perception, Maga suggested that color might not have any effect on salt perception because salty foods can come in any color, and hence, people have few direct color associations with saltiness.

Maga (1974) argued that there is a natural correlation between redness and sweetness levels as many fruits ripen. That is, many fruits show a transition from colors at the green end of the spectrum, through yellow, to colors at the red end of the spectrum (see also Brice 1954; Kostyla 1978; Lavin and Lawless 1998; Zampini et al. 2007 on this point). Maga suggested that prior exposure to this natural color–taste correlation (i.e., between increases in redness and sweetness in foods) might help explain why red/green coloring should have such a profound effect on sweetness/sourness perception. Consistent with this suggestion, Pangborn (1960) demonstrated that the addition of green food coloring reduced sweetness ratings while enhancing sourness ratings in pear nectar, though it should be noted that Pangborn and Hansen (1963) subsequently failed to replicate this finding. A consistent pattern of results has been reported more recently in a study by Lavin and Lawless (1998). The participants in this study were given four strawberry-flavored drinks of different colors (light and dark red and light and dark green) to rate for sweetness using a nine-point categorical scale. The participants rated the dark red solutions as sweeter than light red solutions, but light green solutions as sweeter than dark green solutions.

While the results discussed thus far in this section would appear to demonstrate that the addition (vs. absence) of food coloring leads to a significant effect on ratings of the presence (vs. absence; Johnson and Clydesdale 1982; Maga 1974) of sweetness and that increasing the intensity

Table 2 Summary of the results from Maga's (1974) study highlighting the effect of the addition of color on participants' sensitivity to each of the four traditional basic tastants when dissolved in solution (and compared to performance when the tastants were presented in uncolored solutions)

Color of solution	Taste			
	Sour (citric acid)	Sweet (sucrose)	Salty (sodium chloride)	Bitter (caffeine)
Red	No effect	No effect	No effect	Decrease
Yellow	Decrease	Decrease	No effect	No effect
Green	Decrease	Increase	No effect	No effect

of color can increase perceived sweetness intensity ratings (Johnson and Clydesdale 1982; Johnson et al. 1982, 1983; Roth et al. 1988), it is important to note that many other studies have failed to demonstrate any such effect (see Alley and Alley 1998; Christensen 1985; Frank et al. 1989; McCullough et al. 1978; Pangborn 1960; see also Johnson and Clydesdale 1982). For example, Alley and Alley reported no effect of the addition of color (red, blue, yellow, and green) when compared to a clear, no-color-added baseline on participants' ratings of the sweetness of either sweetened water or gelatine samples. Similarly, Frank et al. (1989) reported that adding red food coloring to either an odorless or strawberry odor-sweetened aqueous samples failed to increase perceived sweetness ratings of the orange red-looking drinks relative to participants' assessment of the clear drinks. Note that the participants in this latter study had to rate the intensity of 16 stimuli on a 21-point sweetness scale: the stimuli were generated by crossing the factors of sweetness intensity (four levels), color (present vs. absent), and odorant (present vs. absent). In other words, half of the drinks in this study were uncolored. This raises the possibility that the inclusion of so many sweetened but uncolored solutions might have helped participants to realize that the color was not necessarily predictive of the presence/intensity of the taste. A similar explanation could, of course, also be put forward to account for the null results reported by Alley and Alley (1998). Zampini et al. (2007) also failed to demonstrate an easily interpretable effect of variations in color intensity on perceived sweetness intensity using a labeled magnitude scale rating procedure.

Thus, with regard to the question of whether or not adding color to an otherwise colorless substrate influences the perceived *intensity* of different basic tastes, the answer appears to depend on a number of factors including the particular taste under investigation (Maga 1974) and perhaps the precise presentation protocol adopted (such as how many incongruently colored trials the participant may be presented with; see footnote 4). Certainly, magnitude estimation typically gives rise to more pronounced effects than other methods (though see Gifford and Clydesdale 1986 for one null effect of color on salt perception reported using the magnitude estimation technique). The consensus view would currently seem to be that color cues do not influence the perception of saltiness (see Chan and Kane-Martinelli 1997; Gifford and Clydesdale 1986; Gifford et al. 1987; Maga 1974). By contrast, the perception of sweetness can be modified by the addition of red (or green) food coloring (e.g., see Johnson et al. 1982, 1983; Kostyla 1978; Lavin and Lawless 1998; Pangborn 1960), but importantly, this effect is not always observed (Alley and Alley 1998; Frank et al. 1989; Johnson 1982; McCullough et al. 1978; Pangborn 1960). Null effects are often reported in studies in which colored drinks are compared to clear drinks (though see Zampini et al. 2007 for an exception).

Taken at face value, these results would appear to suggest that color does indeed influence people's perception of taste intensity. However, under closer examination, many of the findings reported above are potentially problematic. For example, in their description of the threshold task, Johnson and Clydesdale (1982) make no reference to interleaving any "catch trials" in which unsweetened solutions were mixed in with the sweetened solutions. This is unfortunate because of the susceptibility to *response bias*; that is, it could be argued that the presence of the coloring in certain solutions simply led the participants in those studies to expect a taste to be present, and thus, they were more willing to respond that they did indeed perceive a taste (cf. Engen 1972; Odgaard et al. 2003). It is important to note that the magnitude estimation procedure is also vulnerable to *demand characteristics*; that is, participants could easily be influenced by the coloring such that their responses, rather than their actual taste percepts, changed in response to changes in the color intensity of the solutions (indeed, it seems possible that under certain conditions, participants may simply want to please the experimenter). Using signal detection techniques (e.g., see Green and Swets 1966) could help separate out perceptual from decisional effects here.[3] Due to space constraints, detailing each of the various factors that might help account for the occurrence of false positive results (if that is what Johnson and colleagues' results actually reflect) lies beyond the scope of the present paper; for instance, the specific tasks and ranges of stimuli used in each study, as well as the demand characteristics of each experiment and differences in the pools of participant tested, might all be expected to influence participants' expectations (see Shankar et al. 2009), which could, in turn, have influenced the pattern of results that were observed.

Does food color *influence flavor intensity?* As visual inspection of Table 1 makes clear, there have been far fewer studies of color's influence on perceived flavor intensity. However, in contrast to the rather mixed picture regarding the effect of color on taste intensity, the story concerning color's effect on flavor intensity seems much more clear-cut and convincing. In one of the most frequently cited studies in this area, DuBose et al. (1980) reported that overall flavor intensity was affected by color intensity, with higher color intensity solutions giving rise to stronger flavor evaluation

[3] Perceptual effects are usually defined in terms of a change in perceptual sensitivity, such as a change in the d' measure that can be derived using signal detection theory (e.g., Green and Swets 1966). By contrast, changes in decisional criteria, possibly reflecting a response bias or change in the criteria for responding adopted by participants (such as, for example, participants simply being more likely to respond that a flavor, odor, or taste is present whenever a color is added to a liquid; see Engen 1972), may show up in one's measure of bias (c or beta).

responses by participants for orange- (but not for the cherry-) flavored beverages. Meanwhile, Kostyla (1978) reported that the addition of yellow color to sweetened cherry-, raspberry-, and strawberry-flavored beverages decreased flavor ratings by around 4%. Blue color reduced fruit flavor by 20% (and the addition of red coloring increased sweetness by 5–10%). Elsewhere, significant effects of color on flavor intensity have also been reported by Romeu and De Vicente (1968). More complex results have been reported in other studies where certain color–flavor combinations appear to give rise to bigger effects than others (Bayarri et al. 2001), and null results of varying the intensity of the color on flavor intensity are rarer (Zampini et al. 2007, 2008).

It should be noted here that people are very poor at identifying orthonasally presented odors in the absence of any other sensory cues regarding the odor's identity (e.g., Cain 1979; Desor and Beauchamp 1974; Engen 1972; Eskenazi et al. 1986; Jönsson et al. 2005; Zellner et al. 1991). By contrast, people appear to be much better at identifying the presence of the basic tastes (e.g., sweet, sour, salty, and bitter; see Bartoshuk 1975; Laing et al. 2002). A priori, then, it would seem likely that participants' judgments of odor (and hence of flavor) identity would be much more likely to be influenced by the presentation of an incongruent visual color cue than would their judgments of the identity of a specific tastant.

Indeed, robust effects of color cues on judgments of odor intensity have now been reported in numerous studies (e.g., Blackwell 1995; Davis 1981; Engen 1972; Morrot et al. 2001; Parr et al. 2003; Zellner and Kautz 1990; Zellner and Whitten 1999). For example, Zellner and Whitten reported that the addition of color (presented at one of four different color intensity levels) influenced participants' odor intensity responses when orthonasally sniffing red strawberry and green mint solutions. Interestingly, ratings of the intensity of the strawberry odor peaked at the middle color intensity, while for the mint odor, there was a monotonic increase with increasing color intensity. In a subsequent experiment, Zellner and Whitten showed that while the intensity of the color played a large role in modulating perceived odor intensity, the specific color that was added (be it appropriate or inappropriate) had little effect. Given results such as these, it would seem likely that color should also influence flavor intensity judgments. That said, however, most of these crossmodal studies involved investigating the effect of color on participants' orthonasal odor judgments. In this regard, the results of a study by Koza et al. (2005) are critical. For example, they demonstrated that while the addition of color resulted in an increase in the perceived intensity of orthonasally presented odors, it actually led to a reduction in the perceived intensity of the very same odors when presented retronasally (i.e., as they would be if participants were making flavor judgments; see also Christensen 1983; Zellner and Durlach 2003).

It is worth noting that researchers who have documented *null* results of the addition of food coloring on ratings of taste and/or flavor intensity have rarely bothered to conduct any kind of analysis to ensure they had sufficient power in their experimental design to observe a significant effect had one been present (see Frick 1995). Because of the nature of flavor research, the number of trials a given participant can complete tends to be rather limited,[4] hence constraining the ability of experimenters to detect what may well be a relatively small behavioral effect (see also Lecoutre and Derzko 2001; Rouanet 1996). Complicating this issue even further is the fact that the effects of food coloring on ratings of taste and flavor intensity, or on the detection of the presence of a tastant in solution, appear to be rather stimulus-specific (e.g., see Bayarri et al. 2001; Maga 1974; Zampini et al. 2007, 2008). Note that a similar stimulus specificity has also been reported previously for the case of olfactory–gustatory interactions (e.g., see Frank and Byram 1988; though see also Valentin et al. 2006). It is therefore currently unclear whether the discrepant results of color on taste intensity reported by different groups of researchers over the last 50 years are best explained in terms of a failure to properly control for all of the potential confounding variables or by a lack of statistical power in the experimental designs used by certain researchers in the field; plausible arguments can be made in both directions.

Does Food Color Influence Perceived Flavor Identity?

By contrast, many (and, in fact, we would argue *all*) studies published to date support the claim that judgments of flavor *identity* are influenced by a food's color (e.g., DuBose et al. 1980; Hall 1958; Institute of Food Technologists 1980; Kanig 1955; Levitan et al. 2008; Moir 1936; Sakai 2004; Shankar et al. 2009; Stillman 1993; Zampini et al. 2007, 2008; see also Dolnick 2008; note that we are aware of no studies that have examined the effect of food color on taste identification, and hence in this section, we only discuss studies of color's influence on flavor identification). By contrast, several studies have investigated the effect of color on orthonasal olfactory odor identification judgments. So, for example, Zellner et al. (1991) have shown that participants correctly identify odors more rapidly when colored appropriately than when uncolored or else inappropriately colored.

[4] Note here also that many of the demonstrations of the influence of color on taste and/or flavor in the literature have actually been reported in those studies in which the participants were only given a very small number of stimuli to evaluate (e.g., five or less stimuli in certain of the experiments reported by DuBose et al. 1980; Hoegg and Alba 2007b; Hyman 1983; Lavin and Lawless 1998; Morrot et al. 2001; Oram et al. 1995; Stillman 1993; or 6–15 stimuli in the studies reported by Alley and Alley 1998; Shankar et al. 2009). This may be particularly important as people appear to quickly learn that the color of a beverage no longer predicts a particular taste (see Stevenson et al. 2000).

In terms of studies looking at color's effect on flavor identification, DuBose et al. (1980) conducted one frequently cited study addressing this question. The participants in their study attempted to identify the flavors of a variety of differently colored fruit-flavored drinks. Certain color–flavor pairings were deemed "appropriate" (e.g., a cherry-flavored drink colored red), while others were deemed "inappropriate" (e.g., as when the lime-flavored drink was colored red; though see Shankar et al. 2009 on the notion of appropriateness). DuBose et al. found that participants misidentified the flavor of a number of the drinks when the coloring was inappropriate. What is more, participants' incorrect answers often seemed to be driven by the colors of the drinks themselves. That is, the participants often made what could be classed as *visually dominant* responses (see Partan and Marler 1999; Posner et al. 1976). So, for example, 26% of the participants reported that a cherry-flavored drink tasted of lemon/lime when colored green as compared to no-lime-flavor responses when the drink was colored red instead (see Table 3 for a summary of the results from one of the experiments conducted by DuBose et al.).

One potentially important limitation with regard to the interpretation of the study of DuBose et al. (1980), and, in fact, with the majority of other studies that have investigated crossmodal influences of food coloring on flavor perception in humans (e.g., Hall 1958; Kanig 1955; Moir 1936; Oram et al. 1995), is that the participants were not informed of the deception that was taking place (e.g., see Hall 1958, p. 229). This is a particularly important issue given that it means that the participants in the majority of the studies that have investigated the effect of color on flavor identification may simply have assumed that the colors of the drinks were meant to be informative with regard to their likely flavor. In other words, if participants found it difficult to discriminate the identity of the flavor (or taste) on the basis of gustatory, olfactory, and/or flavor cues, then they may simply have decided to respond on the basis of the more easily discriminable color cues instead. Hence, it is entirely possible that the participants in these studies may simply have used the salient visual cues as a cognitive shortcut with regard to the likely flavors of the foods that they were being asked to evaluate (cf. Bertelson and Aschersleben 1998 for a similar confound that has been identified in the literature documenting the visual capture, or dominance, over perceived auditory localization). That is, the participants in these earlier studies of multisensory flavor perception may have felt some pressure to respond in line with the salient information provided visually (namely, the obviously changing color of the drink from one trial to the next; cf. Orne 1962). As such, it is unclear whether the results reported in many of the early studies demonstrating color's influence on flavor identification responses reflect a *response bias* elicited by the clearly visible (and changing) colors of the drinks that were presented to the participants, a genuine crossmodal *perceptual effect* (i.e., meaning that the color cues actually modulated the flavor percept itself; see Green and Swets 1966; Hoegg and Alba 2007a), or some unknown combination of these two effects (see below for a fuller discussion of this issue).[5]

One means by which researchers have attempted to circumvent (or at least reduce) this potential uncertainty regarding the cause of color's influence on flavor identification responses is by explicitly informing their participants of the potential deception prior to the start of the study (see Stillman 1993; Zampini et al. 2007, 2008). Although only a few studies have, to date, taken this precaution, the results nevertheless confirm the suggestion that food coloring can still affect people's flavor identification responses under such conditions. For example, the 310 untrained observers (visitors to an open day at the University of Auckland) in a study reported by Stillman (1993) were each given a

Table 3 Partial summary of the results from DuBose et al. (1980) (experiment 2)

Reported flavor	Color of drink		
	Red (%)	Orange (%)	Green (%)
Cherry	70	41	37
Orange	0	19	0
Lime	0	0	26

The results highlight the profound effect that food coloring can have on participants' flavor identification responses. The participants in this study had to try and identify 16 different sequentially presented beverages created by fully crossing the factors of flavor (cherry-, orange-, or lime-flavored, or flavorless) and color (red, orange, green, colorless). The participants were given a checklist of 14 possible responses (including 12 fruit flavors) to choose from when trying to identify each of the drinks (strawberry, raspberry, lemon, lime, grape, apple, cherry, orange, blueberry, lemon lime, grapefruit, apricot, other, or no flavor). The table highlights the distribution of responses from the three most common flavor responses for the cherry-flavored drink. The numerical values indicate the percentages of each flavor response for each color

[5] Note that we do not wish to argue that decisional biases in the context of food colorings' influence on multisensory flavor perception are not, in and of themselves, interesting. They most certainly are. Our point here is rather that the decisional biases that are elicited not simply by the color of the foodstuff itself, but rather by the ecologically invalid context in which the participants in these laboratory studies often find themselves, may not be especially informative (see also Garber et al. 2001, 2003 for a similar argument). Our concern is that the results of such studies may say more about how participants respond when placed in an ecologically invalid laboratory context than they do about color's influence on flavor perception in the real world.

beverage to taste and identify and were informed that its color was independent of the flavor. The drinks were either raspberry- or orange-flavored and were either colored red, yellowish orange, green, or else left uncolored. The results (see Fig. 2) showed that participants were significantly better at correctly identifying the raspberry flavor when the drink was colored red than when it was colored green, orange yellow, or else was presented as a colorless solution. The orange-flavored solution was identified significantly more accurately when the drink was colored orange, yellow, or red than when it was presented as a colorless solution.

The participants in another study reported by Zampini et al. (2007; experiment 2) were also explicitly informed that there was *no* relationship between the color and flavor of the drinks that they had to evaluate. That is, they were informed that each of the 124 drinks that they had to sample was just as likely to appear as a colorless solution, or as a red, green, orange, yellow, blue, or gray solution, regardless of its actual flavor. Even though Zampini et al.'s participants were clearly aware that the colors of the drinks that they were tasting were not in any way informative (cf. Engen 1972), the colors of the drinks nevertheless still exerted a significant influence on participants' flavor identification responses (see Fig. 3). Similar results were also reported in a follow-up study (Zampini et al. 2008) in which the participants had to try and identify the flavor of blackcurrant, orange, and flavorless solutions that had been colored yellow, gray, orange, red, or else left colorless (see Fig. 4). Taken together, the results of Zampini et al.'s (2007, 2008) studies therefore add weight to the claim that the crossmodal effect of color on multi-sensory flavor perception in humans does not reflect task demands or any simple form of decisional bias (cf. Delwiche 2004; Hoegg and Alba 2007b).

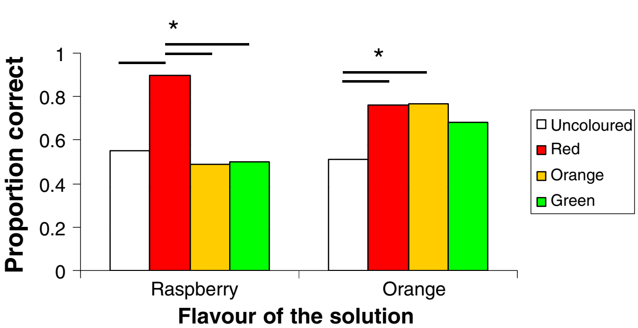

Fig. 2 Summary of the results of Stillman's (1993) study in which 310 participants were given a single drink to taste and identify. The *horizontal lines* indicate those comparisons between conditions that were significant (*asterisk*) using independent samples chi-square tests

Interim Summary

In summary, then, many studies over the last 70 years or so have provided empirical support for the claim that the color of a food/drink can exert a powerful influence on people's flavor *identification* responses (e.g., DuBose et al. 1980; Hall 1958; Kanig 1955; Levitan et al. 2008; Moir 1936; Oram et al. 1995; Shankar et al. 2009; Stillman 1993; Zampini et al. 2007, 2008). What is more, we are *not* aware of any studies that have reported results that conflict with this claim—i.e., where the color of a food was (noticeably) changed but where this change had no effect on participants' flavor identification responses.[6] As such, we would argue that Lavin and Lawless's (1998, p. 284) claim that "the literature on the effects of color on taste and flavour judgments is consistent in its inconsistency" is incorrect for at least as far as the effects of food coloring on people's flavor *identification* responses are concerned, the answer appears clear-cut: food coloring most certainly does influence people's flavor identification responses.

Here, though, it is also important to bear in mind that one does not tend to see complete visual dominance (sometimes known as 'capture'). That is, participants' flavor identification responses do not always match the color that they see. Instead, researchers typically report a visual biasing of participants' responses on a certain proportion of the trials, with the exact proportion varying from one study to the next. So, for example, DuBose et al. (1980) showed that atypically colored drinks were identified by their color on 40% of the trials and by their flavor on 28% of the trials. Meanwhile, the participants in Stillman's (1993) study were able to correctly identify the flavor of the drink in 60% of trials. Oram et al. (1995) reported that for adults tested in their study, responses were based on color on 13% of trials and on flavor on 79% of trials. We discuss possible reasons for this discrepancy below.

Perceptual vs. Decisional Contributions to Color's Influence on Flavor Identification

None of the studies reported thus far bear directly (and unequivocally) on the question of whether these crossmodal effects on participants' flavor identification responses reflect a decisional effect, a perceptual effect, or some

[6] The one exception to this claim comes from one of the conditions in Zampini et al.'s (2007, Experiment 2) study in which participants' flavor identification responses for the strawberry-flavored solutions were not significantly affected by the changes that were introduced into the colors of the drinks. However, given that the numerical trends were in the appropriate direction, this null result may simply reflect a lack of statistical power.

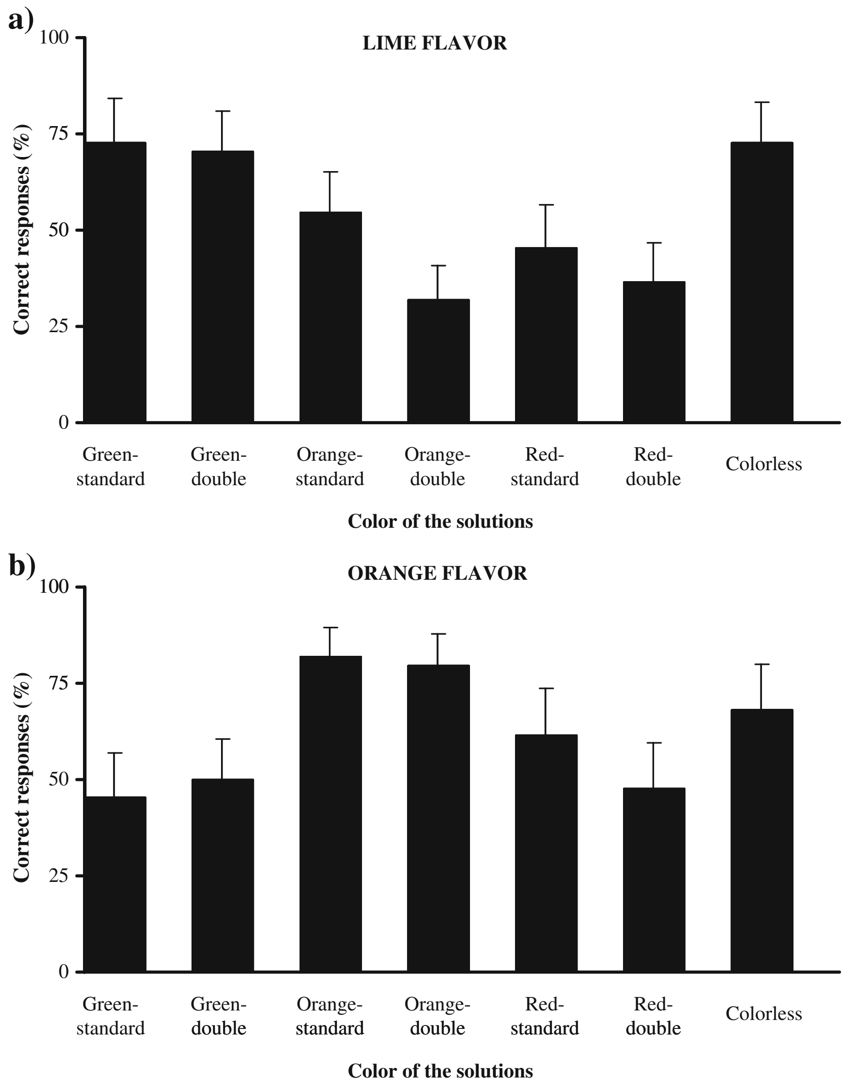

Fig. 3 Summary of the results of the study of Zampini et al (2007) (experiment 2) documenting the effect of color on flavor identification. Lime, orange, strawberry, and flavorless drinks were presented either colored green, orange, red, or colorless in a fully counterbalanced design. Either a standard or double intensity of the colorant was added to the solutions. The participants had to try and identify the flavor of each drink from a list of 22 alternatives (if the participants indicated the "other" option they were prompted to suggest the specific flavor they had in mind) and also rate the flavor intensity. They were given 124 samples to evaluate in total using a sip-and-spit method. Coloring the solutions congruently (e.g., green for lime, red for strawberry, and orange for orange) led to a modest increase in the number of correct flavor identification responses for the strawberry- and orange-flavored drinks (relative to the performance seen when participants judged the colorless solutions). Incongruent coloring impaired the participants' ability to identify the orange- (when colored green or red) and lime-flavored solution (when colored orange or red). Overall, color appeared to have less of an impact on the identification of the strawberry solutions. At present, there is no obvious explanation for this particular result. Note also that it is difficult to discern any clear pattern of results from the doubling of the intensity of the food coloring added to the various solutions

unknown combination of the two. One problem here in terms of trying to answer this question is that there are no simple means of assessing perceptual sensitivity (such as the *d′* measure that is afforded by signal detection theory; Green and Swets 1966) when participants are allowed to make unconstrained flavor identification responses, as often happens when one is trying to identify a food's flavor in natural settings. While it is certainly true that techniques do exist to try and counteract the contribution of any guessing biases that may be present (see Chen and Spence 2010; Intraub 1984), no one has as yet used them in order to try and isolate any genuinely perceptual contribution to color's influence on participants' flavor *identification* responses (see also O'Mahony 1992).

As such, all that can be said with any confidence at the present time is that *all* of the studies that have been published to date (no matter whether using a free responding or forced choice discrimination task) have shown a

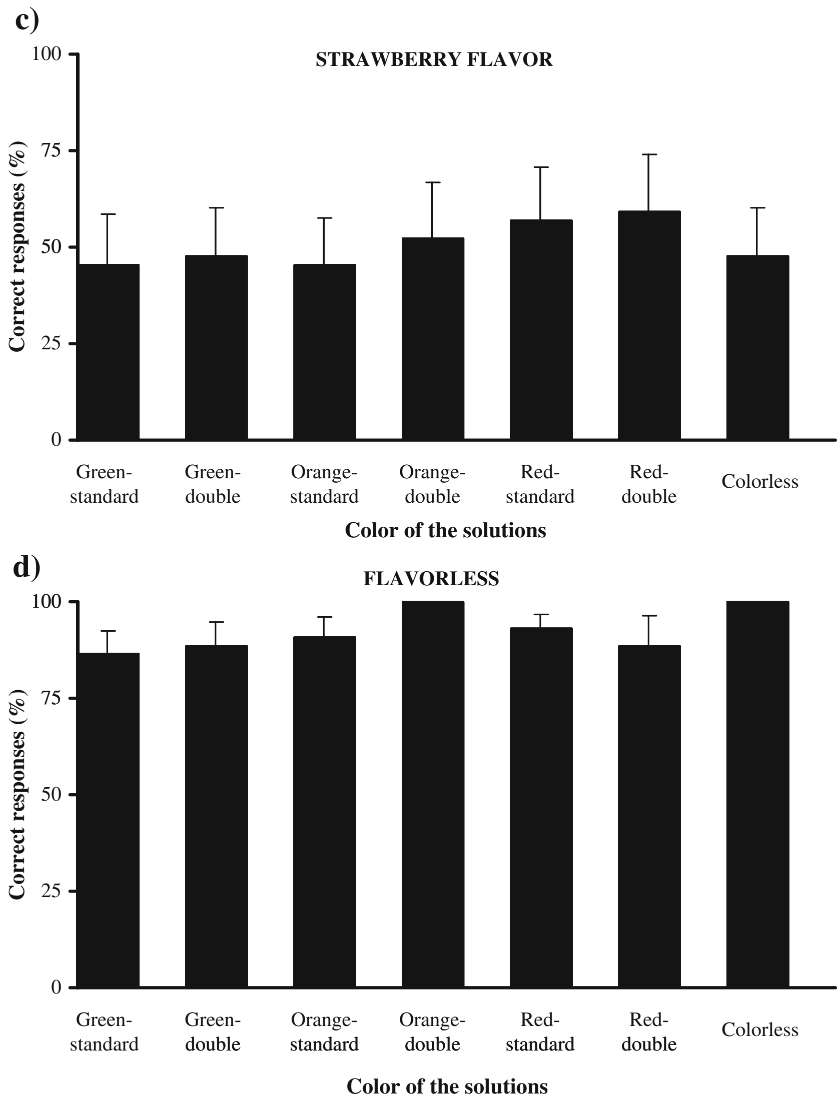

Fig. 3 (continued)

crossmodal effect of color on participants' flavor identification responses. Whether this reflects a genuine perceptual effect, a predominantly decisional effect, or some unknown combination of the two effects will only be resolved by future research. Progress here will likely come through the use of more sophisticated psychophysical paradigms (e.g., see Odgaard et al. 2003 for such an approach being applied to the auditory modulation of visual brightness judgments; see also Lau et al. 1995). It is also possible that a definitive answer to the question of whether or not color's crossmodal influence on flavor identification occurs at a perceptual level may be assisted by the evidence emerging from cognitive neuroscience research. It would, for example, be interesting to know whether the neural activity in primary (or possibly secondary) gustatory cortex and perhaps more interestingly in orbitofrontal cortex elicited by a gustatory/olfactory/flavor stimulus can be changed simply by changing a food or drink's color (cf. González et al. 2006; McClure et al. 2004; Österbauer et al. 2005; Small 2004; Veldhuizen et al. 2009; Verhagen and Engelen 2006). Such effects, should they be observed, would certainly be consistent with the existence of at least some perceptual component to the crossmodal effect of color on flavor perception. Given that such top-down effects have recently been observed on the basis of verbal food/taste descriptors (e.g., Nitschke et al. 2006; Sarinopoulos et al. 2006), we are optimistic that they might also be found here (that is, for the case of visual color cues).

Expectancy-Based Effects of Food Coloring

It seems likely that whenever we see a food of a certain color, that color, together with any other contextual cues (e.g.,

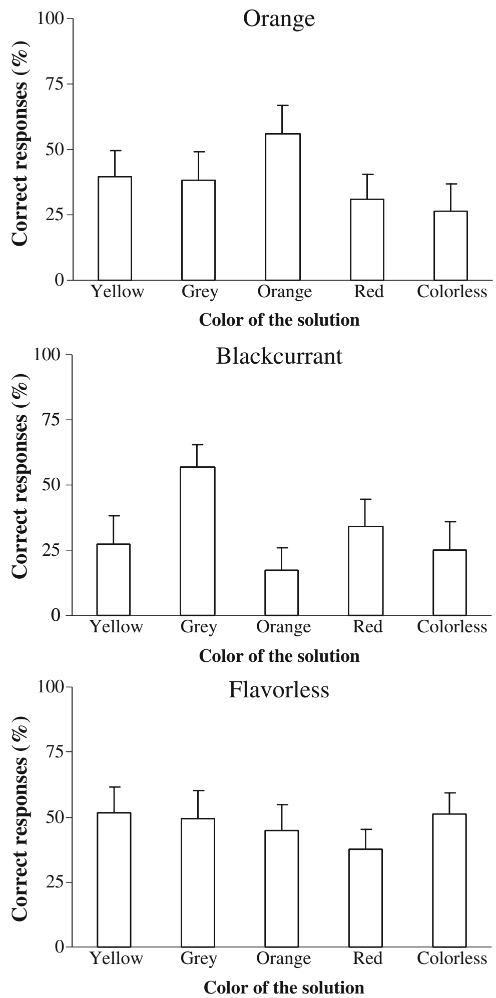

Fig. 4 Summary of the results of the study of Zampini et al. (2008) highlighting the crossmodal effect of color on participants' flavor identification responses. Once again, a sip-and-spit method was used

is it a food or drink item, hot or cold, transparent or opaque, etc; what Francis 1977, describes as "visual appearance" cues), will lead us to generate specific *expectations* regarding the likely flavor of that food (see Cardello 2007; Koch and Koch 2003; Lee et al. 2006; Levitan et al. 2008; Shankar et al. 2009; Yeomans et al. 2008; Zellner and Durlach 2003). Zampini et al. (2007) (experiment 1) recently investigated the nature of these crossmodal associations by showing participants (all from the UK and of UK origin) a range of colored drinks (green, orange, yellow, blue, gray, red, and colorless) and asking them to look at each drink in turn and simply report (without tasting) what flavor they would expect it to have. The results (see Table 4) showed that all of the colored drinks generated systematic expectations regarding a drink's likely flavor. It is our belief that such color-induced flavor expectations (what Hutchings 1977 called "anticipatory" effects) may lead to the "misidentification" of flavors when a drink is subsequently tasted (cf. Stevenson and Oaten 2008). Misidentification at this (cognitive) level will presumably also provide access to a wealth of semantic information about the "misidentified" flavor (see Engen 1972; Gottfried and Dolan 2003; Jönsson et al. 2005; Marques 2006; Morrot et al. 2001; Parr et al. 2002; Revonsuo 1999; Skrandies and Reuther 2008; Zellner et al. 1991), which in turn might reasonably be expected to influence participants' judgments/responses. This misidentification may then have perceptual (i.e., as well as decisional) consequences (see also Williams et al. 1984a, b). Here, one need only think of the placebo effect where a person's beliefs (be they induced by the color of a pill or verbal labeling) have been shown to have surprisingly low-level (i.e., perceptual) effects (de Craen et al. 1996; Plassmann et al. 2008; Shiv et al. 2005).

Regarding the expectancy-based account of color's influence on multisensory flavor perception, it is interesting to note that red, one of the colors that have often been shown to generate strong expectations concerning a food's taste, odor, and flavor (e.g., Koch and Koch 2003; O'Mahony 1983; see also Demattè et al. 2006), also happens to be one of the colors that are most often reported as having an effect in terms of influencing flavor, taste, and odor perception (in terms of both identity and intensity judgments; e.g., Hyman 1983; Johnson and Clydesdale 1982; Maga 1974; Morrot et al. 2001; Oram et al. 1995; Stillman 1993; see Fig. 2). It should, however, also be noted that different colors will likely lead to the generation of different taste/flavor expectations by different people as a function of their background and/or culture (Shankar et al. 2009; see also Scanlon 1985), expertise/experience with tasting a particular foodstuff (e.g., Pangborn et al. 1963; Parr et al. 2003; Smith 2007; Urbányi 1982; Williams et al. 1984a, b; though see also

Table 4 Results of the study of Zampini et al. (2007) (experiment 1) assessing the flavor expectations generated by a group of UK participants on being presented with clear plastic beakers containing transparent drinks that had been colored green, orange, yellow, blue, gray, red, or left colorless

Color of drink	Expected flavor (% of participants with that expectation)
Green	Lime (69%), apple (20%), melon (11%)
Orange	Orange (91%), aniseed (5%), toffee (4%)
Yellow	Lemon (89%), pear (5%), apple (4%), melon (2%)
Blue	Spearmint (86%), raspberry (9%), cream soda (5%)
Gray	Blackcurrant (53%), licorice (40%), cherry (4%), aniseed (4%)
Red	Strawberry (46%), raspberry (27%), cherry (27%)
Colorless	Flavorless (51%), cream soda (16%), vanilla (15%), aniseed (15%), spearmint (2%), melon (2%), pear (2%)

The table shows the percentage of trials in which participants reported that they expected a particular colored drink to taste of a certain flavor

Teerling 1992), and age (Oram et al. 1995; Philipsen et al. 1995; see also Lavin and Lawless 1998).

Shankar et al. (2009) recently investigated the nature of any cross-cultural differences in color–flavor expectancy effects. The two groups of participants in their study, one from the UK the other from Taiwan, were shown seven colored drinks (brown, blue, yellow, orange, green, clear, and red) and had to report on the flavor that they expected each colored drink to taste of. Just as in the study of Zampini et al. (2007), the participants in each group were found to generate consistent flavor expectations based on the colors of the drinks. Importantly, however, the flavor expectations generated by the two groups of participants were significantly different for several (but importantly, not all) of the colored drinks (see Table 5).

Given the individual differences in the flavor expectations generated by viewing a food's coloring, a critical experiment that has yet to be conducted would involve investigating whether the flavor expectations held by an individual do indeed lead to the misidentification of a food or drink's flavor or aroma. Our prediction is that if one person expects a brown drink to taste of cola while another expects a drink of the same color to taste of grape (see Table 5; see also Oram et al. 1995), then adding a brown color to a drink should result in different flavor (aroma) identification responses for these two individuals. While this experiment sounds (and indeed is) very simple, no one has, as yet, measured their participants' flavor (or for that matter taste or odor) expectations and then followed through to investigate whether those expectations do indeed predict the subsequent pattern of flavor (taste or odor) misidentification that results when that color is added to a foodstuff (cf. Cardello 2007; Shankar et al., submitted).

While some researchers appear to believe that such cognitive effects of color on flavor will not have any low-level (e.g., physiological/perceptual) consequences (e.g., see Keast et al. 2004; Fig. 1), others clearly think that color's influence on flavor is perceptual in nature (e.g., see Delwiche 2004; Fig. 1). Discussion here though is complicated by the fact that different researchers appear to use the same terms (e.g., "perceptual") to mean very different things. For example, while Delwiche (2004) (Fig. 1) draws a clear distinction between cognitive and perceptual effects, others appear to view cognitive/expectation effects as being perceptual (as opposed to physical, sensory, or hedonic; see Cardello 1996; Fig. 1). It is therefore important to note that expectancy effects (here one can also think of labeling, pricing, and/or branding as forms of expectancy effect; e.g., Cardello 1994, 2007; Hutchings 1977; Shiv et al. 2005; though see Davis 1981) have been shown in neuroimaging studies to have surprisingly early effects on sensory information processing in humans (e.g., McClure et al. 2004; Nitschke et al. 2006; Plassmann et al. 2008; Sarinopoulos et al. 2006). Such results therefore raise the possibility that color-induced expectancy effects might also influence a person's perceptual representation of flavor information and not just the response that they happen to make.

Color-induced expectancy effects might influence flavor perception (in particular, identification) by directing a participant's *attention* to a salient component of a flavor stimulus (e.g., Ashkenazi and Marks 2004; Marks 2002; Marks and Wheeler 1998; Marshall et al. 2006; Oram et al. 1995). Research elsewhere in psychology has shown that the focusing of a participant's attention on a particular stimulus or stimulus attribute can enhance the perceptual representation of that stimulus or stimulus attribute (i.e., can have an effect on perceptual sensitivity as measured by a change in d'). It is, though, important to bear in mind that color cues can (and do) sometimes lead to decisional effects as well (e.g., by influencing people's criteria for making various judgments; cf. Engen 1972; McCullough et al. 1978). Such decisional effects are likely to be especially prominent when the stimulus itself is ambiguous (as flavor stimuli often are; cf. Chaiken 1980; Wilson and Klaaren 1992). Taken together, the research reviewed in this section therefore supports the view that "higher level" (or top-down) cognitive beliefs or expectations can (and do) have low-level (early) effects.

The Multisensory Integration of Color/Flavor Cues

One of the most important issues for future research concerns the question of whether in addition to any top-down cognitive influence (in the form of expectancy effects), food coloring can also influence flavor identification in humans (automatically) in a bottom-up manner via multisensory integration. The multisensory integration of flavor cues in a food or drink with an atypical visual color cue would be expected to lead to a form of sensory (i.e., visual) dominance over flavor perception (see Ernst and Banks 2002; Ernst and Bülthoff 2004; Posner et al. 1976; Spence 2008). Numerous neurophysiological studies have already demonstrated the integration of olfactory, gustatory, textural, and visual cues in the orbitofrontal cortex of both monkey and man (see Gottfried and Dolan 2003; Österbauer et al. 2005; Rolls and Baylis 1994; Rolls et al. 1996). Given that the Bayesian approach is currently proving so successful elsewhere in the study of multisensory integration, one might expect this approach to understanding multisensory perception to have an influence here as well soon. However, the problem that one soon runs into in terms of trying to separate top-down (i.e., cognitive) and bottom-up (i.e., stimulus-driven) influences is that many of

Table 5 Results of the cross-cultural study of Shankar et al. (2010) assessing the flavor expectations elicited by differently colored drinks in two groups of participants, one from the UK, the other from Taiwan

COLOR	British Participants (N=20)	Taiwanese Participants (N=15)
Brown	Cola (14), Cherry (3), Blackcurrant (2)	Grape (6), Mulberry (3), Cranberry (3)
Blue	Raspberry (8), Mint (4), Blueberry (3)	Mint (7), Cocktail (3)
Yellow	Lemon (11), Pineapple (2), Grape (2)	Yellow Soda (4), White Wine (2)
Orange	Orange (13)	Cranberry (2), Strawberry (2), Apple(2)
Green	Mint (11), Lime (4), Apple (4)	Mint (5), Apple (3), Lime (2), Kiwi (2)
Clear	Water (16), Lemon (2)	Water (14)
Red	Cherry (8), Strawberry (4), Cranberry (3), Raspberry (3),	Cranberry (5), Strawberry (2), Cherry (2), Wine (2)

The table highlights the three most commonly expected flavor responses (chosen by more than one participant). The shaded rows indicate the colored drinks (brown, blue, yellow, and orange) that elicited significantly different flavor expectations from the two groups of participants

the factors that are likely to promote top-down cognitive effects are also likely to increase the likelihood of bottom-up multisensory integration as well (see Spence 2007 on this point).

Isolating the Bottom-Up Effects of Color on Flavor Perception

In the future, though, it may be possible to isolate any bottom-up effects of color on flavor perception by utilizing articulatory suppression to minimize the effect of top-down cognitive factors on participants' performance. For instance, Stevenson and Oaten (2008) recently used this technique in order to investigate whether color's effect on orthonasal olfaction is automatic or not. The cherry and strawberry olfactants used in this study were dissolved in liquids that were colored green, red, or else left colorless. Stevenson and Oaten demonstrated that the crossmodal influence of color (either appropriate or inappropriate) on odor discrimination performance was significantly reduced when their participants engaged in articulatory suppression (saying the word "the" out loud repeatedly) while evaluating the odors. This result suggests that the crossmodal effect of color on odor perception is not mandatory (or, in Stevenson and Oaten's words, "automatic"). As such, it provides some evidence against color influencing odor perception through a process of bottom-up multisensory integration (perhaps leading to sensory dominance) since research in other areas of psychology has shown that multisensory integration tends to be relatively automatic (i.e., unaffected by the performance of a secondary task; see Navarra et al. 2009; Santangelo and Spence 2008 for reviews).

It would, of course, be ideal to utilize the articulatory suppression technique in order to assess whether one can eliminate (or at least modulate) color's crossmodal effect on flavor identification.[7] If one were to obtain a similar result to that reported by Stevenson and Oaten (2008), it would provide evidence that color's influence on flavor perception is mediated primarily by cognitive (or top-down) expectancy factors and not by bottom-up (i.e., automatic) multisensory integration. One might think such a result likely given Stevenson and Oaten's use of food odors. However, it is important to note that Koza et al. (2005) have shown that color can have qualitatively different effects on olfactory perception as a function of whether an odor is delivered orthonasally (as in Stevenson and Oaten's study) or retronasally (as when actually consuming a food or drink). Alternatively, however, one may also be able to dissociate

[7] Though, of course, there may be some practical challenges associated with trying to taste a colored solution while at the time speaking out loud. One could though instead ask the participant to read out a list of words silently in their head or else to engage in some other highly attention-demanding task, for example, monitoring a rapid serial visual presentation stream for occasionally presented targets (e.g., see Santangelo and Spence 2008).

bottom-up multisensory integration effects from top-down effects resulting from cognitive expectancies by playing with the parameters of stimulus presentation, such as by varying the timing and/or spatial relationship between the color and the flavor (see also Lee et al. 2006). Bottom-up integration tends to be more sensitive to spatiotemporal coincidence of the constituent signals than are top-down cognitive effects (see Spence 2007).

It may, of course, turn out that the crossmodal effect of food coloring on flavor identification operates in both a top-down manner via cognitive expectations and in a bottom-up manner via the sensory dominance resulting from the automatic (i.e., involuntary) multisensory integration of the various unimodal sensory signals. Complicating matters further here though is the fact that the relative contribution of top-down and bottom-up factors might also vary as a function of the specific combinations of color (and other visual appearance cues; Francis 1977; Levitan et al. 2008) and flavor being investigated. On the one hand, the more that a color is associated with a particular taste or flavor (such as red being associated with sweetness in ripe fruits and green with tartness/sourness in unripe fruits; Maga 1974; Pangborn 1960), the stronger one might expect that both the bottom-up and top-down effects should be. By contrast, the consequences of marketing, for example, the recent introduction of the association between blue coloring and raspberry flavoring (see Garber et al. 2008; Shankar et al. 2010; see also Triplett 1994), might, at least initially, be expected to have a primarily cognitive effect.

Having demonstrated that food coloring does indeed influence flavor identification, the question of how best to unravel the various mechanism(s), at both a behavioral and neural level, underlying this crossmodal effect clearly represents an important and challenging area for study in the years to come. Part of the challenge here comes from the fact that (as shown in Fig. 1) it is currently unclear whether color's crossmodal influence on flavor perception in any given situation is being driven by color's influence on taste, smell (orthonasal or retronasal), or directly on the flavor percept itself. What is, though, certain at the present time is that color plays an integral part in our experience of, and responses toward, food and drink even if, as suggested by the ISO (1992, 2008), visual cues do not constitute a core attribute of flavor perception.

References

Alley RL, Alley TR (1998) The influence of physical state and color on perceived sweetness. J Psychology: Interdisciplinary Applied 132:561–568

Ashkenazi A, Marks LE (2004) Effect of endogenous attention on detection of weak gustatory and olfactory flavors. Percept Psychophys 66:596–608

Auvray M, Spence C (2008) The multisensory perception of flavor. Conscious Cogn 17:1016–1031

Bartoshuk LM (1975) Taste mixtures: is mixture suppression related to compression? Physiol Behav 14:643–649

Bayarri S, Calvo C, Costell E, Duran L (2001) Influence of color on perception of sweetness and fruit flavor of fruit drinks. Food Sci Technol Int 7:399–404

Bertelson P, Aschersleben G (1998) Automatic visual bias of perceived auditory location. Psychon Bull Rev 5:482–489

Blackwell L (1995) Visual clues and their effects on odour assessment. Nutr Food Sci 5:24–28

Brice BA (1954) Color and its relationship to food investigations. In Farrell KT, Wagner JR, Peterson MS, MacKinney G (eds) Color in foods: A symposium sponsored by the Quartermaster Food and Container Institute for the Armed Forces Quartermaster Research and Development Command U. S. Army Quartermaster Corps. National Academy of Sciences - National Research Council: Washington, pp. 4–16

Cain WS (1979) To know with the nose: keys to odor identification. Science 203:467–470

Cardello AV (1994) Consumer expectations and their role in food acceptance. In: MacFie HJH, Thomson DMH (eds) Measurement of food preferences. Blackie Academic & Professional, London, pp 253–297

Cardello AV (1996) The role of the human senses in food acceptance. In: Meiselman HL, McFie HJH (eds) Food choice, acceptance and consumption. Blackie Academic & Professional, New York, pp 1–82

Cardello AV (2007) Measuring consumer expectations to improve food product development. In: MacFie HJH (ed) Consumer-led food product development. Woodhead Publishing, Cambridge, pp 223–261

Chaiken S (1980) Heuristic vs systematic information processing and the use of source versus message cues in persuasion. J Pers Soc Psychol 29:752–766

Chan MM, Kane-Martinelli C (1997) The effect of color on perceived flavor intensity and acceptance of foods by young adults and elderly adults. J Am Diet Assoc 97:657–659

Chen Y-C, Spence C (2010) When hearing the bark helps to identify the dog: semantically-congruent sounds modulate the identification of masked pictures. Cognition 114:389–404

Christensen C (1983) Effects of color on aroma, flavor and texture judgments of foods. J Food Sci 48:787–790

Christensen C (1985) Effect of color on judgments of food aroma and food intensity in young and elderly adults. Perception 14:755–762

Davis RG (1981) The role of nonolfactory context cues in odor identification. Percept Psychophys 30:83–89

de Craen AJ, Roos PJ, Leonard de Vries A, Kleijnen J (1996) Effect of colour of drugs: systematic review of perceived effect of drugs and of their effectiveness. Br Med J 313:1624–1626

de Wijk RA, Polet IA, Engelen L et al (2004) Amount of ingested custard dessert as affected by its color, odor, and texture. Physiol Behav 82:397–403

Delwiche J (2004) The impact of perceptual interactions on perceived flavor. Food Qual Prefer 15:137–146

Demattè ML, Sanabria D, Spence C (2006) Cross-modal associations between odors and colors. Chem Senses 31:531–538

Desor J, Beauchamp G (1974) The human capacity to transmit olfactory information. Percept Psychophys 16:551–556

Dolnick E (2008) Fish or foul? The New York Times, September 2. Downloaded from http://www.nytimes.com/2008/09/02/opinion/02dolnick.html?_r=1&scp=1&sq=chocolate%20strawberry%20yogurt&st=cse on 07/07/09

DuBose CN, Cardello AV, Maller O (1980) Effects of colorants and flavorants on identification, perceived flavor intensity, and hedonic quality of fruit-flavored beverages and cake. J Food Sci 45:1393–1399, 1415

Duncker K (1939) The influence of past experience upon perceptual properties. Am J Psychol 52:255–265

Engen T (1972) The effect of expectation on judgments of odour. Acta Psychol 36:450–458

Ernst MO, Banks MS (2002) Humans integrate visual and haptic information in a statistically optimal fashion. Nature 415:429–433

Ernst MO, Bülthoff HH (2004) Merging the senses into a robust percept. Trends Cogn Sci 8:162–169

Eskenazi B, Cain WS, Friend K (1986) Exploration of olfactory aptitude. Bull Psychon Soc 24:203–206

Fletcher L, Heymann H, Ellersieck M (1991) Effects of visual masking techniques on the intensity rating of sweetness of gelatins and lemonades. J Sens Stud 6:179–191

Francis FJ (1977) Color and appearance as dominating sensory properties of food. In: Birch GG, Brennan JG, Parker KJ (eds) Sensory properties of foods. Applied Science, Barking, pp 45–47

Frank RA, Byram J (1988) Taste–smell interactions are tastant and odorant dependent. Chem Senses 13:445–455

Frank R, Ducheny K, Mize S (1989) Strawberry odor, but not red color, enhances the sweetness of sucrose solutions. Chem Senses 14:371–377

Frick RW (1995) Accepting the null hypothesis. Mem Cogn 23:132–138

Frost MB, Janhoj T (2007) Understanding creaminess. Int Dairy J 17:1298–1311

Garber LL Jr, Hyatt EM, Starr RG Jr (2001) Placing food color experimentation into a valid consumer context. J Food Prod Mark 7(3):3–24

Garber LL Jr, Hyatt EM, Starr RG Jr (2003) Measuring consumer response to food products. Food Qual Prefer 14:3–15

Garber LL Jr, Hyatt EM, Boya ÜÖ (2008) The mediating effects of the appearance of nondurable consumer goods and their packaging on consumer behavior. In: Schifferstein HNJ, Hekkert P (eds) Product experience. Elsevier, London, pp 581–602

Gifford SR, Clydesdale FM (1986) The psychophysical relationship between color and sodium chloride concentrations in model systems. J Food Prot 49:977–982

Gifford SR, Clydesdale FM, Damon RA Jr (1987) The psychophysical relationship between color and salt concentrations in chicken flavored broths. J Sens Stud 2:137–147

González J, Barros-Loscertales A, Pulvermüller F, Meseguer V, Sanjuán A, Belloch V et al (2006) Reading *cinnamon* activates olfactory brain regions. NeuroImage 32:906–912

Gottfried JA, Dolan RJ (2003) The nose smells what the eye sees: crossmodal visual facilitation of human olfactory perception. Neuron 39:375–386

Green DM, Swets JA (1966) Signal detection theory and psychophysics. Wiley, New York

Hall RL (1958) Flavor study approaches at McCormick and Company, Inc. In: A. D. Little Inc. (ed) Flavor research and food acceptance: a survey of the scope of flavor and associated research, compiled from papers presented in a series of symposia given in 1956–1957. Reinhold, New York, pp 224–240

Hoegg J, Alba JW (2007a) Linguistic framing of sensory experience: there is some accounting for taste. In: Lowrey TM (ed) Psycholinguistic phenomena in marketing communications. Erlbaum, Mahwah, pp 3–21

Hoegg J, Alba JW (2007b) Taste perception: more than meets the tongue. J Consum Res 33:490–498

Hutchings JB (1977) The importance of visual appearance of foods to the food processor and the consumer. In: Birch GG, Brennan JG, Parker KJ (eds) Sensory properties of foods. Applied Science Publishers, London, pp 45–57

Hyman A (1983) The influence of color on the taste perception of carbonated water preparations. Bull Psychon Soc 21:145–148

Institute of Food Technologists (1980) Food colors. J Food Technol 34 (7):77–84

Intraub H (1984) Conceptual masking: the effects of subsequent visual events on memory for pictures. J Exp Psychol Learn Mem Cogn 10:115–125

ISO (1992) Standard 5492: terms relating to sensory analysis. International Organization for Standardization

ISO (2008) Standard 5492: terms relating to sensory analysis. International Organization for Standardization

Johnson J (1982) Psychophysical relationships between colour and sweetness in fruit flavored solutions. Ph.D. thesis. University of Massachusetts at Amherst

Johnson J, Clydesdale FM (1982) Perceived sweetness and redness in colored sucrose solutions. J Food Sci 47:747–752

Johnson JL, Dzendolet E, Damon R, Sawyer M, Clydesdale FM (1982) Psychophysical relationships between perceived sweetness and color in cherry-flavored beverages. J Food Prot 45:601–606

Johnson JL, Dzendolet E, Clydesdale FM (1983) Psychophysical relationships between perceived sweetness and redness in strawberry-flavored beverages. J Food Prot 46:21–25, 28

Jönsson FU, Tchekhova A, Lönner P, Olsson MJ (2005) A metamemory perspective on odor naming and identification. Chem Senses 30:353–365

Kanig JL (1955) Mental impact of colors in foods studied. Food Field Reporter 23:57

Keast RSJ, Dalton PH, Breslin PAS (2004) Flavour interactions at the sensory level. In: Taylor AJ, Roberts DD (eds) Flavour perception. Blackwell Scientific, Oxford, pp 228–255

Koch C, Koch EC (2003) Preconceptions of taste based on color. J Psychol: Interdisciplinary Applied 137:233–242

Kostyla AS (1978) The psychophysical relationships between color and flavor of some fruit flavored beverages. PhD thesis, University of Massachusetts, Amherst

Koza BJ, Cilmi A, Dolese M, Zellner DA (2005) Color enhances orthonasal olfactory intensity and reduces retronasal olfactory intensity. Chem Senses 30:643–649

Laing DG, Link C, Jinks AL, Hutchinson I (2002) The limited capacity of humans to identify the components of taste mixtures and taste–odour mixtures. Perception 31:617–635

Lau K-N, Post G, Kagan A (1995) Using economic incentives to distinguish perception bias from discrimination ability in taste tests. J Mark Res 32:140–151

Lavin J, Lawless H (1998) Effects of color and odor on judgments of sweetness among children and adults. Food Qual Prefer 9:283–289

Lecoutre B, Derzko G (2001) Asserting the smallness of effects in ANOVA. Methods Psychological Research 6:1–32

Lee L, Frederick S, Ariely D (2006) Try it, you'll like it: the influence of expectation, consumption, and revelation on preferences for beer. Psychol Sci 17:1054–1058

Levitan C, Zampini M, Li R, Spence C (2008) Assessing the role of color cues and people's beliefs about color–flavor associations on the discrimination of the flavor of sugar-coated chocolates. Chem Senses 33:415–423

Maga JA (1974) Influence of color on taste thresholds. Chem Senses Flavor 1:115–119

Marks LE (2002) The role of attention in chemosensation. Food Qual Prefer 14:147–155

Marks LE, Wheeler ME (1998) Attention and the detectability of weak taste stimuli. Chem Senses 23:19–29

Marques JF (2006) Specialization and semantic organization: evidence for multiple semantics linked to sensory modalities. Mem Cogn 34:60–67

Marshall K, Laing DG, Jinks AL, Hutchinson I (2006) The capacity of humans to identify components in complex odor–taste mixtures. Chem Senses 31:539–545

Masurovsky BI (1939) How to obtain the right food color. Food Eng 11:13, 55–56

McClure SM, Li J, Tomlin D, Cypert KS, Montague LM, Montague PR (2004) Neural correlates of behavioral preference for culturally familiar drinks. Neuron 44:379–387

McCullough JM, Martinsen CS, Moinpour R (1978) Application of multidimensional scaling to the analysis of sensory evaluations of stimuli with known attribute structures. J Appl Psychol 63:103–109

Moir HC (1936) Some observations on the appreciation of flavour in foodstuffs. J Soc Chem Ind: Chemistry Industry Review 14:145–148

Morrot G, Brochet F, Dubourdieu D (2001) The color of odors. Brain Lang 79:309–320

Navarra J, Alsius A, Soto-Faraco S, Spence C (2009) Assessing the role of attention in the audiovisual integration of speech. Inf Fusion 11:4–11

Nitschke JB, Dixon GE, Sarinopoulos I, Short SJ, Cohen JD, Smith EE et al (2006) Altering expectancy dampens neural response to aversive taste in primary taste cortex. Nat Neurosci 9:435–442

Norton WE, Johnson FN (1987) The influence of intensity of colour on perceived flavour characteristics. Med Sci Res 15:329–330

O'Mahony M (1983) Gustatory responses to nongustatory stimuli. Perception 12:627–633

O'Mahony M (1992) Understanding discrimination tests: a user-friendly treatment of response bias, rating and ranking R-index texts and their relationship to signal detection. J Sens Stud 7:1–47

Odgaard EC, Arieh Y, Marks LE (2003) Cross-modal enhancement of perceived brightness: sensory interaction versus response bias. Percept Psychophys 65:123–132

Oram N, Laing DG, Hutchinson I, Owen J, Rose G, Freeman M, Newell G (1995) The influence of flavor and color on drink identification by children and adults. Dev Psychobiol 28:239–246

Orne MT (1962) On the social psychology of the psychological experiment: with particular reference to demand characteristics and their implications. Am Psychol 17:776–783

Österbauer RA, Matthews PM, Jenkinson M, Beckmann CF, Hansen PC, Calvert GA (2005) Color of scents: chromatic stimuli modulate odor responses in the human brain. J Neurophysiol 93:3434–3441

Pangborn RM (1960) Influence of color on the discrimination of sweetness. Am J Psychol 73:229–238

Pangborn RM, Hansen B (1963) The influence of color on discrimination of sweetness and sourness in pear-nectar. Am J Psychol 76:315–317

Pangborn RM, Berg HW, Hansen B (1963) The influence of color on discrimination of sweetness in dry table-wine. Am J Psychol 76:492–495

Parr WV, Heatherbell D, White KG (2002) Demystifying wine expertise: olfactory threshold, perceptual skill and semantic memory in expert and novice wine judges. Chem Senses 27:747–755

Parr WV, White KG, Heatherbell D (2003) The nose knows: influence of colour on perception of wine aroma. J Wine Res 14:79–101

Partan S, Marler P (1999) Communication goes multimodal. Science 283:1272–1273

Philipsen DH, Clydesdale FM, Griffin RW, Stern P (1995) Consumer age affects response to sensory characteristics of a cherry flavoured beverage. J Food Sci 60:364–368

Plassmann H, O'Doherty J, Shiv B, Rangel A (2008) Marketing actions can modulate neural representations of experienced pleasantness. Proc Natl Acad Sci USA 105:1050–1054

Posner MI, Nissen MJ, Klein RM (1976) Visual dominance: an information-processing account of its origins and significance. Psychol Rev 83:157–171

Revonsuo A (1999) Binding and the phenomenal unity of consciousness. Conscious Cogn 8:173–185

Rolls ET, Baylis LL (1994) Gustatory, olfactory, and visual convergence within the primate orbitofrontal cortex. J Neurosci 14:5437–5452

Rolls ET, Critchley HD, Mason R, Wakeman EA (1996) Orbitofrontal cortex neurons: role in olfactory and visual association learning. J Neurophysiol 75:1970–1981

Romeu JV, De Vicente MLS (1968) Influyen los colores en el sabor? [Do colours influence flavour?]. Rev Interam Psicologia 2:143–157

Roth HA, Radle LJ, Gifford SR, Clydesdale FM (1988) Psychophysical relationships between perceived sweetness and color in lemon- and lime-flavored drinks. J Food Sci 53(1116–1119):1162

Rouanet H (1996) Bayesian methods for assessing importance of effects. Psychol Bull 119:149–158

Sakai N (2004) The effect of visual stimuli on perception of flavor. Poster presented at ISOT 2004

Santangelo V, Spence C (2008) Is the exogenous orienting of spatial attention truly automatic? Evidence from unimodal and multisensory studies. Conscious Cogn 17:989–1015

Sarinopoulos I, Dixon GE, Short SJ, Davidson RJ, Nitschke JB (2006) Brain mechanisms of expectation associated with insula and amygdala response to aversive taste: implications for placebo. Brain Behav Immun 20:120–132

Scanlon BA (1985) Race differences in selection of cheese color. Percept Mot Skills 61:314

Shankar MU, Levitan CA, Prescott J, Spence C (2009) The influence of color and label information on flavor perception. Chemosensory Perception 2:53–58

Shankar MU, Levitan CA, Spence C (2010) Does higher level knowledge mediate the interpretation of multisensory cues? Conscious Cogn (in press)

Shiv B, Carmon Z, Ariely D (2005) Placebo effects of marketing actions: consumers may get what they pay for. J Mark Res XLII:383–393

Skrandies W, Reuther N (2008) Match and mismatch of taste, odor, and color is reflected by electrical activity in the human brain. J Psychophysiol 22:175–184

Small DM (2004) Crossmodal integration—insights from the chemical senses. Trends Neurosci 27:120–123

Smith BC (ed) (2007) Questions of taste: the philosophy of wine. Oxford University Press, Oxford

Spence C (2007) Audiovisual multisensory integration. Acoust Sci Technol 28:61–70

Spence C (2008) Multisensory perception. In: Blumenthal H (ed) The big fat duck cook book. Bloomsbury, London, pp 484–485

Stevenson RJ (2009) The psychology of flavour. Oxford University Press, Oxford

Stevenson RJ, Oaten M (2008) The effect of appropriate and inappropriate stimulus color on odor discrimination. Percept Psychophys 70:640–646

Stevenson RJ, Boakes RA, Wilson JP (2000) Resistance to extinction of conditioned odor perceptions: evaluative conditioning is not unique. J Exp Psychol Learn Mem Cogn 26:423–440

Stillman J (1993) Color influences flavor identification in fruit-flavored beverages. J Food Sci 58:810–812

Strugnell C (1997) Colour and its role in sweetness perception. Appetite 28:85

Teerling A (1992) The colour of taste. Chem Senses 17:886

Tom G, Barnett T, Lew W, Selmants J (1987) Cueing the consumer: the role of salient cues in consumer perception. J Consum Mark 4 (2):23–27

Triplett T (1994) Consumers show little taste for clear beverages. Marketing News 28(11):2, 11

Urbányi G (1982) Investigation into the interaction of different properties in the course of sensory evaluation. I. The effect of colour upon the evaluation of taste in fruit and vegetable products. Acta Aliment 11:233–243

Valentin D, Chrea C, Nguyen DH (2006) Taste–odour interactions in sweet taste perception. In: Spillane W (ed) Optimising sweet taste in foods. Woodhead Publishing Limited, Cambridge, pp 66–84

Veldhuizen MG, Nachtigal DJ, Small DM (2009) Taste cortex contributes to odor quality coding. Chem Senses 34:A8

Verhagen JV, Engelen L (2006) The neurocognitive bases of human multimodal food perception: sensory integration. Neurosci Biobehav Rev 30:613–650

Williams AA, Langren SP, Noble AC (1984a) Influence of appearance on the assessment of aroma in Bordeaux wines by trained assessors. J Inst Brew 90:250–253

Williams AA, Langron SP, Timberlake CF, Bakker J (1984b) Effect of colour on the assessment of ports. Int J Food Sci Technol 19:659–671

Wilson T, Klaaren K (1992) Expectation whirls me round: the role of affective expectations on affective experiences. In: Clear MS (ed) Review of personality and social psychology: emotion and social behavior. Sage, Newbury Park, pp 1–31

Yeomans M, Chambers L, Blumenthal H, Blake A (2008) The role of expectancy in sensory and hedonic evaluation: the case of smoked salmon ice-cream. Food Qual Prefer 19:565–573

Zampini M, Sanabria D, Phillips N, Spence C (2007) The multisensory perception of flavor: assessing the influence of color cues on flavor discrimination responses. Food Qual Prefer 18:975–984

Zampini M, Wantling E, Phillips N, Spence C (2008) Multisensory flavor perception: assessing the influence of fruit acids and color cues on the perception of fruit-flavored beverages. Food Qual Prefer 19:335–343

Zellner DA, Durlach P (2003) Effect of color on expected and experienced refreshment, intensity, and liking of beverages. Am J Psychol 116:633–647

Zellner DA, Kautz MA (1990) Color affects perceived odor intensity. J Exp Psychol Hum Percept Perform 16:391–397

Zellner DA, Whitten LA (1999) The effect of color intensity and appropriateness on color-induced odor enhancement. Am J Psychol 112:585–604

Zellner DA, Bartoli AM, Eckard R (1991) Influence of color on odor identification and liking ratings. Am J Psychol 104:547–561