RUNNING HEAD: MAXIMIZING ODOUR-INDUCED TASTE ENHANCEMENT

Factors affecting odour-induced taste enhancement

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ABSTRACT

Reducing the use of calorific sweeteners in sugar-sweetened beverage while, at the same time, maintaining the perceived sweetness is an important issue for the food industry given the growing global obesity crisis, and the need for many consumers around the world to reduce their sugar intake. A number of fruit aromas/volatiles appear to offer a promising route to enhancing the perception of sweetness without adding to the calorific load. However, while a growing body of empirical evidence suggests that this is a promising strategy, as made clear by this narrative review, there are a number of outstanding questions that have yet to be answered in terms of optimising the impact on sweetness offered by the addition of volatile aromas. It is, for example, currently unclear what the maximum sweetness enhancement effect that can be achieved by combining a variety of different volatiles (e.g., those associated with different fruits) before a ceiling or saturation effect is reached. It is also currently unclear how important conscious awareness of the specific volatiles, or aromas, are to odour-induced taste enhancement (OITE) effects. A third outstanding issue concerns whether OITE would occur in the case of olfactory metamers that do not overlap in terms of their volatile composition. One other intriguing issue concerns whether volatiles only come to be associated with taste qualities as a result of associative learning or whether there are some odours that are, for example, naturally (or innately) sweet.

KEYWORDS: SWEETNESS ENHANCEMENT; FLAVOUR VOLATILES; SMELLED SWEETNESS; MULTISENSORY INTEGRATION; CROSSMODAL PERCEPTION; SUGAR-SWEETENED BEVERAGES.

1. Introduction

While sweet constitutes one of the four or five basic tastes, it has long been recognized that various food odours (often referred to as aromas) are also described as smelling sweet too (see Stevenson & Boakes, 2004, for a review). What is more, when added to beverages, various volatile aromas have been shown to enhance the perception of the associated taste (e.g., sweet). Researchers refer to this effect in terms of 'odor-induced changes in taste perception' (OICTP; Djordjevic, Zatorre, & Jones-Gotman, 2004), or, more frequently, 'odour-induced taste enhancement' (OITE; Nasri, Beno, Septier, Salles, & Thomas-Danguin, 2011). This narrative review summarizes the growing body of empirical research on volatile aromas and their influence on taste perception, with a focus on sweetness, and reducing the sugar content of sweetened beverages (see Ellson, 2017). I also highlight a number of important questions to which we do not yet have an answer as far as maximizing OITE is concerned.

According to the dominant view, food odours acquire their taste-enhancing qualities/associations as a result of co-exposure in foods that are strongly associated with that taste. So, for instance, most people readily describe vanilla, caramel, and strawberries as smelling sweet (Dravnieks, 1985). Vanilla is particularly interesting in this regard as vanilla pods actually taste very bitter. However, the presence of vanilla essence in a diverse range of sweet products from ice-cream to cola beverages mean that it has come to be associated with sweetness for the majority of consumers (Sakai et al., 2001). What is more, adding vanilla flavouring provides an effective means of enhancing sweetness (e.g., in ice cream where the cold temperature may suppress the ability to taste sweetness; see Bartoshuk, Rennert, Rodin, & Stevens, 1982; Lipscomb, Rieck, & Dawson, 2016). North American research from Blank and Mattes (1990) has shown that the sweetness associated with various spices differ between white and non-white participants. For example, nutmeg, a spice which delivers no noticeable taste (Fincks, 1886), was rated as noticeably sweeter by non-white than by white North American participants due, or so the researchers suggested, to this spice being used differently in the cuisines of the two groups (see also Nguyen, Valentin, Ly, Chrea, & Sauvageot, 2001; van der Klaauw & Frank, 1994, on cultural/individual differences in the taste properties associated with various aromas).

An extensive body of research from Stevenson and his colleagues in Australia over the last quarter of a century has helped to establish the limiting conditions on the acquisition of such taste, and taste-enhancing, properties – such as that they can occur following no more than a single co-exposure when participants are exposed to a novel (or unfamiliar) odorant (Prescott, Johnstone, & Francis, 2004), and the fact that the olfactory/taste stimuli do not need to be perceived consciously (that is, they can be presented at a sub-threshold level) when paired and the volatile aroma will often still acquire its ability to influence perceived taste (e.g., Stevenson, Boakes, & Prescott, 1998; Stevenson, Prescott, & Boakes, 1995; Stevenson, Prescott, & Boakes, 1999). By contrast, associating a familiar odour that has previously been associated with one taste, with a different taste, takes much longer (see Stevenson & Boakes, 2004, for a review; cf. Stevenson & Case, 2003). Intriguingly, neither chefs nor wine experts appear to be able to consciously discount the influence of olfaction on judgments of the taste of food and drink (Boakes & Hemberger, 2012; Harrar, Smith, Deroy, & Spence, 2013; though see also Bingham, Birch, de Graaf, Behan, & Perring, 1990). While such acquired taste properties have been described by certain researchers as a form of learned 'olfactory-synaesthesia' (Stevenson & Boakes, 2004; Stevenson, Boakes, & Prescott, 1998; Stevenson & Tomiczek, 2007), the analogy/description has been criticised as misleading/inappropriate by Auvray and Spence (2008).

One potential fly in the ointment as far as the suggestion that odours rapidly acquire taste properties relates to a recent failure to demonstrate the acquisition of sweet taste associations in a study of chewing gum conducted by Fondberg, Lundström, and Seubert (2021). In particular, these researchers found that repeated exposure to an unfamiliar odorant (basil or orange flower) in the context of a chewing gum were not judged any sweeter after repeated exposure to sweetened, as compared to unsweetened, chewing gum. The participants in this particular study chewed each of the gums three times a day over a period of five days for 60 seconds (i.e., six gums were chewed in total per day). To be clear, increased exposure/familiarity led to increased liking, but there was no evidence of associative learning for the odour paired with the sweet taste. It is, though, worth noting that chewing gum is a very special food inasmuch as no matter how much you chew it, the consistency/texture doesn't change. It is unclear whether this may be relevant as far as the lack of evidence of associative learning is concerned. Indeed, in the case of mint gum, it has been shown that even though the aroma may be physically present in the mouth (as revealed by in-nose gas chromatography), it may not be perceived consciously unless there also happens to be a sweet taste in the mouth (Davidson, Linforth, Hollowood, & Taylor, 1999). However, limiting chewing to 60 seconds per gum in Fondberg et al.'s study is presumably unlikely to have exhausted the gum's sweetness.

The majority of the early studies in which olfactory stimuli have been used to modify the taste of food and drink tended to focus on sweetness, and how volatile aromas could be used to modify the taste of sugar-sweetened beverages (see **Table 1**; see also Wang, Mielby, Junge, Bertelsen, Kidmose, Spence, & Byrne, 2019b; Alcaire, Antúnez, Vidal, Giménez, & Ares, 2017; Bouchard, Hetzel, & Olsen, 1968; Burseg, Camacho, Knoop, & Bult, 2010). Subsequently, it has been demonstrated that different food aromas can also take on the qualities of, and modify, other basic tastes. So, for instance, researchers have documented the existence of volatile-enhanced salty (Batenburg & van der Velden, 2011; Chokumnoyporn, Sriwattana, Phimolsiripol, Torrico, & Prinyawiwatkul, 2015; Djordjevic, Zatorre, & Jones-Gotman, 2004; Kakutani, Narumi, Kobayakawa, Kawai, Kusakabe, Kuneida, & Wada, 2019; Lawrence, Salles, Palicki, Septier, Busch, & Thomas-Danguin, 2011; Lawrence, Salles, Septier, Busch, & Thomas-Danguin, 2009; Manabe, Ishizaki, Yamagishi, Yoshioka, & Oginome, 2014; Nasri et al., 2011; Nasri, Septier, Béno, Salles, & Thomas-Danguin, 2013; Onuma, Maruyama, & Sakai, 2018; Seo, Iannilli, Hummel, Okazaki, Buschhüter, Gerber, Krammer, van Lengerich, & Hummel, 2013; Sinding, Thibault, Hummel, & Thomas-Danguin, 2021; Syarifuddin, Septier, Salles, & Thomas-Danguin, 2016; Thanarungroj & Kongpensook, 2021; though see also Godinot, Pelletier, Labbe, & Martin, 2009), bitter (Caporale, Policastro, & Monteleone, 2004; Labbe, Damevin, Vaccher, Morgenegg, & Martin, 2006), and sour smells (Stevenson, Prescott, & Boakes, 1999).[1]

INSERT TABLE 1 ABOUT HERE

[1] Here, when thinking about sour smells, one might also consider the notion of volatile acidity in wine (https://www.awri.com.au/industry_support/winemaking_resources/laboratory_methods/chemical/va/).

There are presumably also a number of food odours that are capable of enhancing the taste of umami (Niimi, Eddy, Overington, Heenan, Silcock, Bremer, et al., 2014), though multisensory interactions involving the so-called fifth taste have not been so extensively-studied in the West, where many people have, until very recently, been less familiar with the quality/taste (Cecchini, Knaapila, Hoffmann, Federico, Hummel, & Iannilli, 2019; Wertz, 2013). It is further perhaps also worth noting here that a number of researchers have chosen to describe umami as a flavour, rather than a basic taste, given that the former is rated as far more pleasant than the latter by participants (Fuke & Ueda, 1996; McCabe & Rolls, 2007; though see also de Araujo, Kringelbach, Rolls, & Hobden, 2003).[2] Certain odours have been shown to modify mouthfeel properties of cider as well (Symoneaux, Guichard, Le Quéré, Baron, & Chollet, 2015; though see also Tournier, Sulmont-Rossé, Sémon, Vignon, Issanchou, & Guichard, 2009; Yeomans & Boakes, 2016).

Intriguingly, Isogai and Wise (2016, p. 557) have reported that: *"a "sweet-smelling" aroma enhanced the rated sweetness of sucrose and decreased the rated bitterness of sucrose octaacetate (SOA), and that a "bitter-smelling" aroma enhanced the bitterness of SOA and decreased the sweetness of sucrose. Thus, with respect to effects on taste intensity, sweet and bitter aromas mimicked mixture-interactions between sweet and bitter tastes".* In other word, the taste consequences elicited by OITE appear to interact with other tastants in much the same way to at least certain taste-taste interactions (Breslin & Beauchamp, 1997; Gillan, 1993).

Given that gustatory and olfactory stimuli are coded by different receptors as part of distinct sensory systems and have qualitatively different perceptual properties, the assumption amongst food science researchers would appear to have been that aromas can only acquire their taste properties as a result of associative learning based on co-exposure (e.g., Labbe & Martin, 2009). That is, it is widely assumed that there are no innate responses to smells (Bartoshuk & Klee, 2013), except perhaps the avoidance of odours with an irritating trigeminal component, and a few possibly evolutionarily important smells such as blood (Arshamian, Laska, Gordon, Norberg, Lahger, Porada, Jelvez Serra, Johansson, Schaefer, Amundin, Melin, Olsson, Olsson, Stensmyr, & Lundström, 2017). So far, so good; But, one might ask, is this the whole story? That is, can every instance of particular taste qualities being associated with specific odours be explained in terms of learned associations (what are described in terms of congruency or harmony; see Murphy & Cain, 1980), or are there some odours that are inherently (or innately) sweet? And what exactly is the association between a particular odorant smelling sweet and it actually enhancing sweetness (e.g., in a model beverage)?

While it is only natural to assume that smelled sweetness would be highly-correlated with olfactorily-induced sweetness enhancement effects (Stevenson et al., 1999), that is presumably by no means always the case – consider here only how the latter effect has been shown to depend on the particular combination of tastants and odorants that is presented. More pronounced crossmodal/multisensory interactions have been observed in the case of congruent combinations of olfactory and gustatory stimuli (Frank & Byram, 1988; Frank, Shaffer, & Smith, 1991; Noble, 1996; Sakai & Ishihara, 1998), where congruency is determined by co-exposure rather than perceptual similarity (Schifferstein & Verlegh, 1996; though see also

[2] Note here that important distinctions have been highlighted between the multisensory interactions of taste on olfaction that are observed in the case of nutritive and non-nutritive tastants, the former sometimes referred to as alimentary tastes (see Hartley, Liem, & Keast, 2019; Linscott & Lim, 2016).

Labbe & Martin, 2009, for a subtly different definition).[3] However, possibly countering such a view, Bartshuk and Klee (2013) have raised the intriguing possibility that certain volatile aromas in fruit, specifically the more floral notes, may be naturally sweet (if not to us, then at least to other species; such as bees, Dudareva, 2005). Although they fall short of explicitly claiming that certain aromas may be innately sweet to humans, Bartoshuk and her colleagues' suggestion that "nature appears to use different sets of volatiles to enhance sweetness in each fruit" (Bartoshuk, Sims, Colquhoun, & Snyder, 2019, p. 1009) could at least be taken to be raising the possibility that certain volatiles might be innately pleasant/sweet.

2. On the olfactory enhancement of sweetness

2.1. Odour-induced sweetness enhancement: Basic findings

Some of the earliest reports suggesting that volatiles were capable of influencing sweetness perception (Murphy, Cain, & Bartoshuk, 1977; see also Blakeslees, 1935) were treated with scepticism (Lawless & Heymann, 1997). For instance, Clark and Lawless (1994) suggested that rather than demonstrating sweetness enhancement, the phenomenon might, in fact, simply reflect 'halo dumping' instead. This is the name given to the possibility that a participant asked to rate the sweetness of a complex flavour sensation is not given the opportunity to rate the other sensations (such as, for example, 'fruitiness') then they may simply choose to dump their experience of the change in these other sensations/attributes onto the sweet response category in order to express themselves (see also Frank, van der Klaauw, & Schifferstein, 1993). Clark and Lawless supported this suggestion by showing that odour-induced sweetness enhancement effects were significantly reduced when participants rated both fruitiness and sweetness as compared to another group of participants who only rated sweetness (see **Figure 1**). Though note that significant taste-enhancement is still observed even in those participants for whom the halo-dumping account has effectively been ruled out.

INSERT FIGURE 1 ABOUT HERE

Given subsequent findings, one might consider whether varying the number of response dimensions in this time-intensity study may have biased participants toward more of an analytic versus synthetic tasting strategy. Importantly, though, the halo dumping account has been ruled out in a number of subsequent studies that have demonstrated sweetness enhancement even when the participants rated fruitiness as well as sweetness (Noble, 1996). Several studies have shown that the attentional strategy/instructions (e.g., whether participants adopt a synthetic or analytic approach to tasting) also matter to the taste-enhancement effects that are observed (Frank, van der Klaauw, & Schifferstein, 1993; Frank, Wessel, & Shaffer, 1990; Labbe et al., 2006; Prescott et al., 2004). One might also consider to what extent sweetness enhancement should be considered as a crossmodal, or multisensory perceptual effect, or rather as a cognitive effect (Noble, 1996; Salles, 2006), meaning that consumers expect products having a particular aroma to taste a certain way. After all, such expectancy effects have been shown to modify the taste of sweetness (cf. Wilton, Stancak, Giesbrecht, Thomas, & Kirkham, 2018). What is more, the fact that Nasri et al. (2011) observed that the addition of sardine aroma to salty aqueous

[3] Here, it is also interesting to consider the question of whether the format, or food, in which tastants and olfactory stimuli happen to be delivered might also constrain, or modulate, which particular combinations count as congruent. This question has not been addressed formally by food science researchers to date.

solutions increased the perceived saltiness of low and medium intensity solutions but not of high intensity salt solution might be considered in terms of the expected saltiness level associated with a particular aroma intensity. When such taste expectations are not met in a beverage, they may lead to a disconfirmation of expectation response (see Johnson, Dzendolet, Damon, Sawyer, & Clydesdale, 1982; Labbe et al., 2006; see Piqueras-Fiszman & Spence, 2015, for a review).

The early studies of volatile-enhanced sweetness tended to focus on fruity volatiles/flavourings, such as ethyl butyrate (strawberry-like) (Murphy, Cain, & Bartoshuk, 1977), strawberry extract (Frank, Ducheny, & Mize, 1989; Stevenson et al., 1999), citral (Murphy & Cain, 1980), peach (Cliff & Noble, 1990), raspberry, passion fruit, and lychee (Stevenson et al., 1999), pineapple (Delwiche & Heffelfinger, 2005), and pomegranate (Wang et al., 2019a). Adding specific 'sweet' tomato volatiles to partly deodorized tomato purees has also both been shown to increase sweetness ratings of trained sensory panellists (Baldwin, Goodner, Plotto, Pritchett, & Einstein, 2004). Interestingly, however, the researchers involved in these various studies have not made any attempt to combine sweet aromas in order to try and enhance the crossmodal effect (Bartoshuk et al., 2019). What is more, at least according to Bartoshuk and her colleagues, the sweetness-enhancing effects reported in these studies have generally been rather small in magnitude (though see Wang et al., 2019b, for a rather different conclusion).

2.2. One perceived natural aroma equals many volatile organic compounds

At this point, it is important to consider the fact that the majority of natural/processed food aromas are actually made up of several hundred different volatile organic compounds. For example, according to Maarse (1983), apple juice contains something like 137 different volatiles (cf. Dimick & Hoskin, 1983), while fresh tomatoes may contain several hundred volatile, of which around 30 are thought to contribute to the flavour (Buttery, 1993; Buttery, Teranishi, Flath, & Ling, 1989). Fermented products such as coffee and wine, by contrast, have been estimated to contain as many as 600-1,000 distinct volatiles (see Spence, 2021, for a review). The question therefore becomes one of whether it is the perceived apple aroma that is associated with, and may be capable of enhancing, sweetness, or whether instead it is some number, or combination, of the component volatiles that are doing the work (see also De Kok, 2017; Knoop, Bult, & Smit, 2009). Potentially relevant here, Dunkel, Steinhaus, Kotthoff, Nowak, Krautwurst, Schieberle, and Hofmann (2014) have highlighted the fact that a relatively small number of what they call key food odours (KFOs) actually deliver the majority of the aroma/flavour of most foods The latter researchers have argued that there may, in fact, only be something like 226 KFOs across all foods, 16 of which have been found in 25% of all food and beverage products (see Dunkel et al. for a list of KFOs). It is interesting to consider the relation between KFOs and sweet-enhancing volatiles (Spence, 2021). Indeed, relatively few of the volatiles in fruits appear to contribute to sweetness (Goff & Klee, 2013; Stevens, Kader, Albright-Houlton, & Algazi, 1977; Watada & Aulenbach, 1979) (see **Figure 2**).

INSERT FIGURE 2 ABOUT HERE

One of the interesting questions here that has not, as least far as I am aware, been addressed is what happens to OITE in the case of olfactory metamers (Ravia, Snitz, Honigstein, Finkel, Zirler, Perl, Secundo, Laudamiel, Harel, & Sobel, 2020). Olfactory metamers occur when different combinations of volatile chemicals give rise to the same perceptual experience. Thus, assuming that an olfactory stimulus that was food-safe in both of its metameric forms could be identified, then such stimuli could presumably be used to help discriminate between the relative importance of the mere presence of specific volatiles and the perception of a sweet-smelling aroma in terms of inducing any odour-induced sweetness enhancement effect.

2.3. Key fruit volatiles associated with sweetness

According to an intriguing line of research from Linda Bartoshuk and her colleagues on enhanced plant breeding (e.g., Gilbert, Guthart, Gezan, Pisaroglo de Carvalho, Schwieterman, Colquhoun, . . . Olmstead, 2015), different volatiles in fruits, such as tomatoes and strawberries, are independently associated with sweetness (Bartoshuk, Blandon, Clark, Colquhoun, Hudson, Klee, Moskowitz, Sims, Snyder, & Tieman, 2012; Bartoshuk, Dreyer, Klee, Odabasi, Sims, Snyder, & Tieman, 2014; Colquhoun, Schwieterman, Snyder, Stamps, Sims, Odabasi, . . . Bartoshuk, 2015; Schwieterman, Colquhoun, Jaworski, Bartoshuk, Gilbert, Tieman, . . . Clark, 2014). Intriguingly, this raises the possibility that different olfactory stimuli can potentially be combined to deliver enhanced sweetness. According to Bartoshuk et al. (2019), more than 100 sweetness-enhancing volatiles have been discovered thus far. To date, for instance, around 12 compounds are known to be associated with sweetness in tomatoes, including the volatile apocarotenoid geranial and 2-methylbutanal, and 3-methyl-1-butanol (Bartoshuk et al., 2012; Bartoshuk et al., 2019; Bartoshuk & Klee, 2013; Vogel, Tieman, Sims, Odabasi, Clark, & Klee, 2010; Tieman et al., 2012). Particularly surprising was the observation that some but by no means all of the volatiles that enhanced sweetness perception were fruity. Isovaleric acid (which is variously described as smelling like ripe cheese or sweaty trainers) was found to enhance sweetness. Meanwhile, β-ionone, another of the sweet volatiles is one to which a large proportion of the population turn out to be functionally anosmic (Plotto, Barnes, & Goodner, 2006; Tieman et al., 2012). The importance of these volatiles have mostly been established in the fruit matrix by combining sensory and instrumental measurements and performing multiple regression analyses. Analysis of tomatoes, blueberries, oranges, and peaches has revealed the key sweetness-enhancing volatiles in each fruit are different (Baldwin, Goodner, & Plotto, 2008; Bartoshuk, 2016; Bartoshuk, Baldwin, Bai, Colquhoun, Klaben, Odabasi, . . . Snyder, 2018; Gilbert et al., 2015; Tieman et al., 2012; see also Ong & Acree, 1998). Meanwhile, Schwieterman et al. (2014) have identified 24 volatiles associated with sweetness in strawberries.

Barba et al. (2018) used gas chromatography and olfactory-associated taste analysis to establish which volatiles were associated with different taste properties in a multi-fruit juice. Nine compounds were associated with sweetness in the juice. Their results demonstrated that the perception of sweetness was significantly enhanced by the presence of ethyl 2-methylbutanoate, furaneol and γ-decalactone in 7% sucrose solution, and in 32% sugar-reduced fruit juice by the presence of ethyl 2-methylbutanoate. However, it should be noted that the limits on combining sweet volatiles from many different fruits are currently unknown. That is, we do not know how many different sweet aromas can be combined before one reaches a ceiling effect in terms of sweetness enhancement. It will be important to address this issue in future research in order to get a better handle on the limits on OITE. Note here also how combining different volatiles is likely to change the perceptual qualities of the resulting mixtures in unpredictable ways.

2.4. Combining cues to sweetness

While the literature shows that adding a variety of different aromas can enhance sweetness, a number of other important questions are still left open. For instance, will adding different sweet aromas together lead to enhanced sweetness perception? It is difficult to say, a priori, given that humans (and that includes experts) have been shown to be very poor at identifying the components of odour mixtures (see Spence & Wang, 2018, for a review). For instance, in one influential study, Laing and Francis (1989) demonstrated that as the number of equi-intense odorants in a mixture increased (up to five), the ability of participants to identify each of the odorants decreased. Many subsequent studies have similarly documented the limited ability of humans to identify the components of odour mixtures or odour-taste mixtures. However, one assumption here is that it is the conscious awareness of the component odours rather than the mere presence of the volatile, or particular constellation of volatiles, that does the work in terms of eliciting OITE effects. However, it is important to recognize that this need not necessarily be the case. For instance, Labbe, Rytz, Morgenegg, Ali, and Martin (2007) have demonstrated that certain olfactory stimuli (such as ethyl butyrate) can enhance sweetness when presented at a subthreshold level (though this is by no means always the case; see Bingham, Birch, de Graaf, Behan, & Perring, 1990; Labbe & Martin, 2009). In a conference abstract, Colquhoun et al. (2015) assessed the impact of adding tomato- and/or strawberry volatiles to a 2% sucrose solution. Individually both the tomato and strawberry volatiles increased the rated sweetness of the drink. Strikingly, combining the two groups of volatiles increased the sweetness of the solution to a much greater extent, that is, the volatile effect added, such that in combination, the sweetness of the solution was nearly doubled.

While some researchers have studied the effects of combining sweet aromas, others have instead wanted to study the effects of combining cues associated with sweetness in different sensory modalities, such as a sweet aroma, a sweet colour (pink; see Spence, Wan, Woods, Velasco, Deng, Youssef, & Deroy, 2015), and even sweet sonic seasoning (Blecken, 2017; Spence, 2017). Intriguingly, Junge (2019) reported that combining pomegranate with red colour or pectin (to add viscosity) led to enhanced sweetness in an apple-elderflower drink relative to when either sweet odour was presented individually (as reported in Junge, Mielby, Bertelson, Byrne, & Kidmose, 2019; Wang, Mielby, Junge, Bertelsen, Kidmose, Spence, & Byrne, 2019c). Meanwhile, the results of a study reported by Wang et al. (2019c) along just these lines revealed that the perceived sweetness of a fruity beverage increased when a sweet pomegranate aroma was added to an apple-elderflower fruit beverage (by 10.9%) and when sweet, rather than bitter, sonic seasoning added or when no music way playing (again 10.9%). In Wang et al.'s study, combining sweet aroma with the sweet sonic seasoning led to an 18.2% increase in sweetness (i.e., the sweetness enhancement effects were more-or-less additive) (see **Figure 3**). The colour of the iPad screen had no effect on sweetness ratings though (see also Frank et al., 1989, for evidence that adding colour to a drink does not always enhance the sweetness of sucrose solutions; see also van Beilen, Bult, Renken, Stieger, Thumfart, Corneliseen, & Kooijman, 2011).[4] One potential advantage of combining various cues to sweetness from different sensory modalities is that the cues do not mask or interfere with one another as can happen when multiple flavour volatiles are combined. However, at present, the limit on the maximum benefit (or rather sweetness enhancement) that can be achieved by combining different sweet aromas/volatiles, or different sensory cues to sweetness, is not known.

INSERT FIGURE 3 ABOUT HERE

2.5. Sweet volatiles: Associative learning versus natural association

The evidence that has been published to date suggests that associative learning is one of the key mechanisms by which olfactory stimuli come to take on specific taste properties. However, some researchers have started to question whether certain (especially floral) notes in fruit volatiles might be innately sweet (see Bartoshuk & Klee, 2013).[5] Indeed, it has been suggested that many of the most important flavour-associated volatiles in fruits are linked to essential nutrients (cf. Goff & Klee, 2006). It is, though, difficult to rule out the possibility that consumers may simply pick up on the statistical correlations in the marketplace between the presence of specific (combinations of) fruit volatiles and the sweetness of the fruit. Relevant in this regard, Bartoshuk and Klee (2013, p. R374) pose the following question: “Although it is clear that olfactory affect is easily learned, is there any evidence that some odorants evoke affect that is hard-wired?” Should certain olfactory stimuli innately be described as sweet? The sweet smell of roses provides an interesting case to consider in this context. While the smelled sweetness in this case has, on occasion, been explained in terms of prior exposure to Turkish delight (given that some versions of this sticky sweet confection are fragranced by rosewater), that doesn’t seem to be the whole story (Batu & Kirmaci, 2009). Note that it has been suggested that roses smell sweet due to the presence of the monoterpene geraniol (Magnard, Roccia, Caissard, Vergne, Sun, Hecquet, et al., 2015). Given that the distinctive sweet smell of roses is made up of multiple volatiles, one might wonder why, exactly, geraniol is the one that becomes associated with sweetness.

In other cases, while not innate, volatiles may acquire their associations very early in development. Just take, for example, the vanillin in breast milk. It has been suggested to be part of the reason why chocolate, which also contains vanillin, is so widely liked (see Ayabe-Kanamura, Schicker, Laska, Hudson, Distel, Kobayakawa, & Saito, 1998; cf. Varendi, Porter, & Winberg, 1996). Other studies, meanwhile, have demonstrated that the foods consumed by pregnant mothers can lead to olfactory preferences at birth (Schaal, Marlier, & Soussignan, 2000). The existence of such learning effects in utero obviously makes it harder to demonstrate convincingly any innate responses to odorants.

Of course, sometimes there may be similarity-based association (Jones, Roberts, & Holman, 1978; Ravia et al., 2020). Rotting corpses smell sickly-sweet. The smell in this case associated

[4] In future research, it might be interesting to investigate the sound symbolic taste of brand names too (see Pathak & Calvert, 2020)

[5] Aristotle apparently distinguished between those odours that were pleasant because they were associated with the nutritive value of food, and a second group of odours, that only in humans that were “agreeable in their essential nature, e.g., those of flowers” (cf. Beare, 1906).

with the presence of certain phenols (Costandi, 2015; Williams, 2015). In this case, presumably the smell is similar to that of something else that we have tasted which was itself sweet. Again, though, one might want to distinguish between the perceived aroma, and the presence of certain specific key volatiles.

One other possibility here that is perhaps worth considering relates to the crossmodal influence of positive affect on taste perception (Wang & Spence, 2018). There would appear to be some evidence for chemical structure determining the perceived pleasantness of unfamiliar odorants (Kermen, Chakirian, Sezille, Joussain, Le Goff, Ziessel Chastrette Mandairon Didier Rouby, & Bensafi, 2011). As such, it might be possible to argue that certain fruit volatiles are naturally pleasant, and that this natural predisposition to pleasantness might, in turn, indirectly be linked to sweetness. That said, the pleasantness based account does not immediately fit with the example of isovaleric acid enhancing sweetness in tomatoes as reported by Bartoshuk and Klee (2013), as mentioned earlier, since this volatile compound is typically described as smelling like sweaty trainers or ripe cheese.

3. Further issues with measuring OITE

Researchers who have studied OITE traditionally tended to present the odours orthonasally. However, recent studies have more often involved the retronasal presentation of odour instead (see Bartoshuk et al., 2012; Isogai & Wise, 2016; Onuma et al., 2018). Here it is important to note that it is retronasal olfaction that is primarily involved in multisensory flavour perception (see Spence, Smith, & Auvray, 2015), whereas orthonasal olfaction is thought to play an important role in setting our flavour expectations instead (see also Rozin, 1982; Wilson, 2021). It is somewhat surprising, therefore, to find that the OITE has been demonstrated regardless of the route (orthonasal or retronasal) by which olfactory stimuli happen to be delivered. At the same time, however, this ‘surprising’ observation fits into a wider body of empirical research showing that olfactory-gustatory interactions are surprisingly insensitive to the route by which olfactory stimuli are administered.

It should also be pointed out here that the majority of the evidence for OITE has been obtained from psychophysical studies conducted on neurologically-normal adult human participants. However, it is legitimate to ask whether OITE also has physiological consequences similar to those seen in those who actually consume the relevant tastants (e.g., sugar). One might also wonder whether neuroscience studies would show any modification of the neural response in primary taste areas as a result of OITE. After all, cognitively-induced sweetness expectancy effects have been shown to modify the brain’s response to the taste of sweetness in the insula, which is considered as the brain’s primary taste area (Wilton et al., 2018; Woods, Lloyd, Kuenzel, Poliakoff, Dijksterhuis, & Thomas, 2011; see also Nitschke, Dixon, Sarinopoulos, Short, Cohen, Smith, Kosslyn, Rose, & Davidson, 2006).

Relevant in this regard, Seo et al. (2013) have demonstrated neural effects of odour-induced saltiness enhancement using functional neuroimaging. In particular, their research revealed that a salty-congruent combination of odour and taste resulted in a significant increase in neuronal activation in those brain areas that are known to be associated with the integration of odour and taste stimuli (e.g., insula, frontal operculum, anterior cingulate cortex, and orbitofrontal cortex) when compared to an incongruent combination and/or odourless air combined with a taste solution. Meanwhile, Onuma et al. (2018) used functional near-infrared spectroscopy (fNIRS) to demonstrate the enhancement of saltiness perception induced by soy sauce aroma. They found that adding soy sauce aroma enhanced the hemodynamic response in temporal brain regions, including the frontal operculum, though no effect was detected on the hemodynamic salivary responses (i.e., a biophysical measure). Probing the impact of odours that have been associated with specific tastes using other physiological and biophysical markers would therefore also appear to be an interesting direction for future research (cf. He, Boesveldt, de Graaf, & de Wijk, 2014; Rousmans, Robin, Dittmar, & Vernet-Maury, 2000; Xu, Hamid, Shepherd, Kantono, Reay, Martinez, & Spence, 2019; Xu, Hamid, Shepherd, Kantono, & Spence, 2019).

Given that adding sweetness to a product tends to lead to increased consumption, future research will need to focus on the question of whether similar effects on consumption behaviour, over either the short or long-term, can be demonstrated as a result of odour-induced sweetness enhancement. I am not aware of any research having been published on this important question as yet (though see Deardorff & King, 2014, for one cautionary tale regarding unsupported claims about the impact of aroma on consumption). Another issue that deserves further consideration concerns the sweetness response scales that have been used by researchers (Bertelsen, Mielby, Alexi, Byrne, & Kidmose, 2020), given the fact that individual differences in taster status, has been shown to exert a significant influence over perceived intensity of sweet taste (Marks, Stevens, Bartoshuk, Gent, Rifkin, & Stone, 1988). What is more, there are also well-documented differences in people's hedonic response to sweetness, with sweet-likers, sweet neutral, and sweet-dislikers documented to prefer significantly different levels of sweetness in food products (Frayling, Beaumont, Jones, Yaghootkar, Tuke, Ruth, et al., 2018; Keskitalo, Knaapila, Kallela, Palotie, Wessman, Sammalisto, et al., 2007; Looy, Callaghan, & Weingarten, 1992; Yeomans, Tepper, Rietzchel, & Prescott, 2007). Such individual differences in the world of taste have been argued to make any between-participants comparisons problematic unless the appropriate response scales are used (see Bartoshuk, Fast, & Snyder, 2005). At the same time, however, it is also worth noting that this tends to be more of a problem for between-participants studies, while the majority of the studies reviewed here have tended to use within-participants experimental designs instead.

4. Conclusions

In recent years, there has undoubtedly been growing interest in the use of volatile aromas to modify the taste of commercial food and beverage products, such as in the case of sugar-sweetened beverages (e.g., Reis, Alcaire, Deliza, & Ares, 2017; Stieger & van de Velde, 2013; Wang, Bakke, Hayes, & Hopfer, 2019a; Wang et al., 2019b; see also Velázquez, Vidal, Varela, & Ares, 2020). The focus in this narrative review has been on the use of fruit volatiles to enhance (or maintain, in the case of reduced-sugar beverages) sweetness. However, optimizing (or maximizing) this approach relies on developing a better understanding of why/how certain volatiles come to be associated with particular taste qualities in the first place. And while it has often been assumed that odours always acquire their taste associations as a result of associative learning, some have started to question whether this is necessarily always the case (Bartoshuk & Klee, 2013).

Researchers have started to identify the key volatiles associated with sweetness-enhancement while, at the same time, begun to demonstrate how combining different groups of sweet volatiles associated with different fruits (such as strawberries and tomatoes) can give rise to additive effects (Colquhoun et al., 2015). As yet, however, it is unclear what the limits on adding even more sweetness-associated volatiles might be. Obviously, addressing this question is of key importance for those in the food and beverage industry wanting to reduce the sugar levels in their products without having to compromise on the sweet taste profile that so many consumers like. Maintaining sweetness via the use of sweet volatiles/aromas will hopefully also avoid the various problems that have been documented to be associated with the widespread use of non-nutritive sweeteners (Dubois & Prakash, 2012; Gardner, Wylie-Rosett, Gidding, Steffen, Johnson, Reader et al., 2012; Mattes & Popkin, 2009; Yang, 2010). The possibility of adding sweetness via product-extrinsic olfactory cues (possibly controlled digitally) also looks to expand in the coming years (Aisala, Rantala, Vanhatalo, Nikinmaa, Pennanen, Raisamo, & Sözer, 2020).

Summary of outstanding questions raised and discussed in the text

- How is it that certain aromas come to take on taste qualities? Is associative learning the only mechanism?
- What, exactly, is the relationship between smelled sweetness of volatiles and their sweetness-enhancing properties (e.g., in sugar-sweetened beverages; see Boakes & Hemberger, 2012; Frank et al., 1989; Stevenson et al., 1999)?
- What are the limits to enhancing sweetness perception by combining volatiles that are individually sweet (Bartoshuk et al., 2019)?
- What is the relative importance of perceived olfactory qualities versus the presence of specific volatiles to olfactory-induced sweetness effects (Bartoshuk & Klee, 2013)?
- What happens to acquired sweetness in the case of olfactory metamers (Ravia et al., 2020)?
- Under what conditions are flavour experts better able to discriminate olfactory from gustatory contributions to sweetness (Bingham et al., 1990; Boakes & Hemberger, 2012; Harrar et al., 2013)?
- How long-lasting are the effects of olfaction on sweetness perception? Will a sweet aroma start to become less sweet over time if it is repeatedly experienced paired with a reduced-sugar beverage?
- What exactly is the relationship between olfactory influences on taste and gustatory influences on smell (e.g., Dalton, Doolittle, Nagata, & Breslin, 2000; Delwiche & Heffelfinger, 2005; see also Crocker, 1945; Gillan, 1983; Shaffer & Frank, 1990)?

Resolving the above questions will likely help to clarify the conditions under which the perception of sweetness can be elicited by OITE, and the limits on such crossmodal effects.

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FIGURE LEGENDS

Figure 1. The halo-dumping effect in time-intensity scaling from Clark and Lawless (1994, Experiment 1). Comparison of open to filled symbols shows the enhancement of sweetness from referred olfactory stimulation. The enhancement with a limited ballot – rating only sweetness – (comparing square symbols) was greater than the enhancement when both sweetness and fruitiness were rated (comparing circles). Notice, though, how a significant sweetness enhancement effect was observed in both groups of participants, i.e., regardless of the possibility of halo dumping. [Figure reprinted from Clark & Lawless (1990, Figure 1), with permission.]

Figure 2. Tomato fruits produce a volatile emission profile that is both attractive to humans and an indicator of ripeness. Of the more than 400 volatiles emitted by tomato fruits, only a small number, almost all of which are derived from essential human nutrients, are detected and integrated into a preferred volatile aroma. This pattern of volatile emissions is mutually beneficial. Thus, volatile emissions are both positive indicators for the presence in the fruit of compounds with positive health benefits and attractants that promote seed dispersal. [Figure reprinted from Goff & Klee (2013, Figure 2), with permission.]

Figure 3. A) Participants' average ratings of sweetness for each sensory condition. Error bars indicate standard errors. Asterisks denote statistical significance (* $p < 0.05$); B) Sweetness enhancement effects (in terms of %) due to soundtrack only, aroma only, or combined soundtrack and aroma conditions. The baseline condition reflects no added aroma and the presentation of the bitter soundtrack. The comparison condition reflects a medium level of added aroma and the presentation of the sweet soundtrack. [Figures reprinted from Wang et al. (2019b, Figures 3 & 4), respectively, with permission.]

Figure 1.

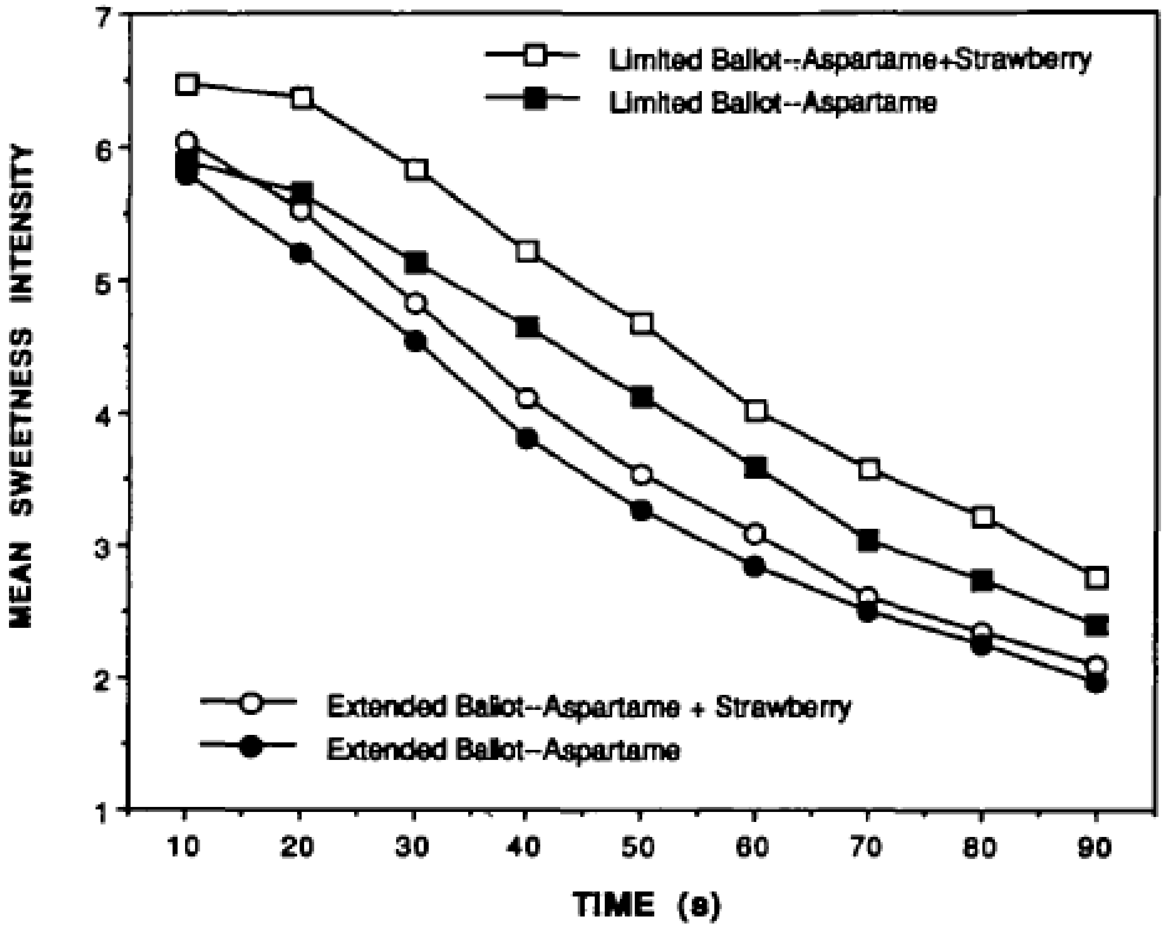


Figure 2.

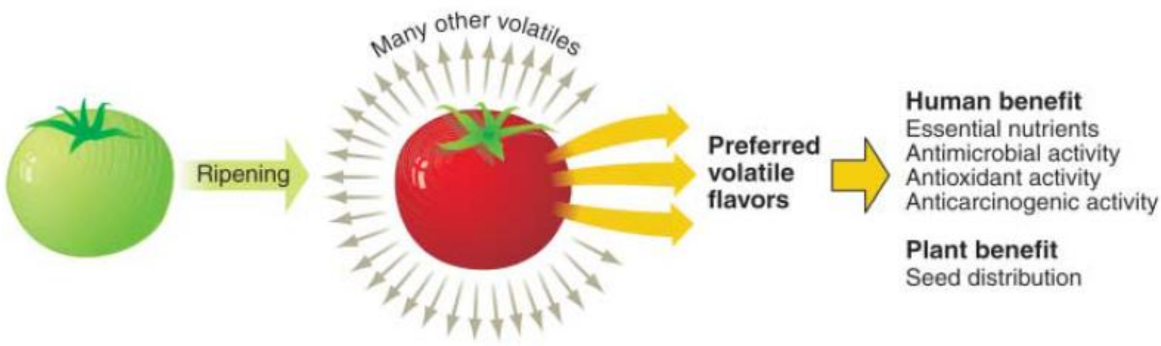
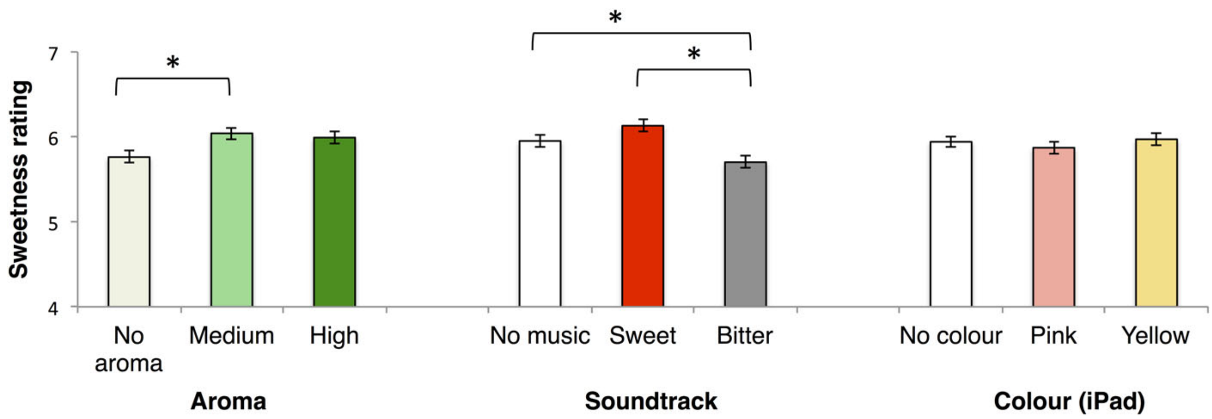
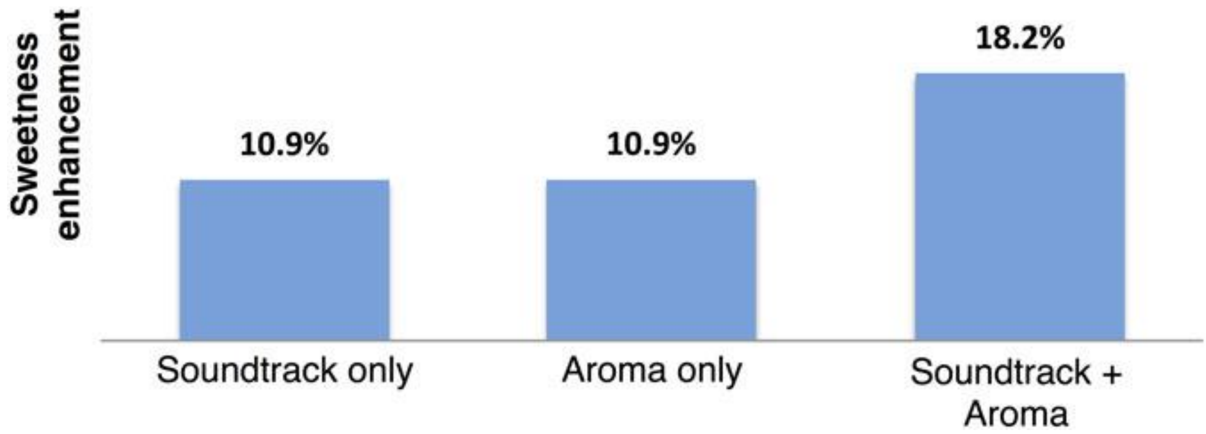


Figure 3.

A)


Sweetness rating
7
6
5
4
*
*
*
No aroma
Medium
High
No music
Sweet
Bitter
No colour
Pink
Yellow
Aroma
Soundtrack
Colour (iPad)

B)


Sweetness enhancement
10.9%
10.9%
18.2%
Soundtrack only
Aroma only
Soundtrack + Aroma