Sweetness Perception of Food/Beverages

Subjects: Food Science & Technology
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When it comes to eating and drinking, multiple factors from diverse sensory modalities have been shown to influence multisensory flavour perception and liking. These factors have heretofore been strictly divided into either those that are intrinsic to the food itself (e.g., food colour, aroma, texture), or those that are extrinsic to it (e.g., related to the packaging, receptacle or external environment).

Keywords: sugar reduction ; multisensory integration ; intrinsic factors ; extrinsic factors ; sweetness perception

1. Introduction

Eating and drinking are amongst the most multisensory of the experiences that we have. When people think about the consumption of food and drink, the senses of taste and smell usually come to mind first. However, a growing body of research conducted over the last decade or two has increasingly demonstrated that *all* of our senses play a role in influencing flavour perception (see References [1][2][3] for reviews). For instance, recalling the experience of eating an apple will usually evoke not just taste and smell, but also its colour, weight, shape, its firmness, crunchiness, juiciness and even the sound of chewing and perhaps its provenance (e.g., supermarket, organic, local, or the tree in the backyard).

A large body of research now supports the view that both *food-intrinsic* sensory factors (e.g., product colour, aroma, texture, viscosity, etc.) as well as *food-extrinsic* factors (e.g., visual, olfactory, and tactile properties of product packaging or servingware, background music, ambient lighting, temperature and aroma, etc.) play a role in determining whether we accept and how we perceive food and beverages (e.g., for intrinsic factors [2][4][5] and for extrinsic factors [6][7][8][9][10][11][12]). What is less clear, however, is how these different factors interact and the relative importance of intrinsic and extrinsic factors to our perception of, not to mention our behaviour towards, food and drink.

In this review, we focus on how intrinsic and extrinsic factors can enhance the perception of sweetness in foods and beverages and address the question of how (and if) they can be combined in order to deliver an enhanced perception of sweetness. The decision to target the perception of sweetness is informed by the growing public health concern over excessive sugar consumption. The consumption of sweet foods has been argued to be one of the major contributors to the current obesity epidemic, with more than 3 million deaths globally each year [13][14][15][16]. Moreover, sugar reduction is of critical concern to major food and beverage companies such as PepsiCo, Givaudan, and Arla, who have been engaging in a number of major initiatives in order to reduce added sugars and develop naturally resourced sweeteners [17][18][19]. Therefore, a multisensory, psychological model of sweetness perception is especially important when it comes to the design of sugar-reduced/replaced foods and beverages.

Hutchings et al. [20] recently outlined four general strategies for sugar reduction. Sugar substitution, altering food structure (e.g., heterogeneously distributing sucrose, modifying tastant release, or reducing particle size), gradual long-term sugar reduction, and using the principles of multisensory integration. However, Hutchings et al. [20] do not address the role of product-extrinsic factors in sweetness perception.

2. Food-Intrinsic versus Food-Extrinsic Influences on Sweetness Perception

In the following section, we will target each sensory modality in turn and review the literature on the intrinsic and/or extrinsic cues regarding their influence on sweetness perception. Table 1 provides a representative summary of studies demonstrating sweetness enhancement effects from the influence of different sensory modalities.

Table 1. A representative selection of studies demonstrating sweetness enhancement via food-intrinsic and extrinsic sensory cues.

Study	Sense	Intrinsic or Extrinsic	Sweet Enhancing Stimuli	Control/Comparison Stimuli	Taste Stimuli	Scale	% Difference
Crisinel et al. (2012) [7]	Hearing	Extrinsic	Sweet soundtrack	Bitter soundtrack	Cinder toffee	1–9 rating (bitter–sweet)	15%
Höchenberger et al. (2018) [21]	Hearing	Extrinsic	Sweet soundtrack	Bitter soundtrack	Toffee	0–100 rating (bitter–sweet)	8%
Höchenberger et al. (2018) [21]	Hearing	Extrinsic	Sweet soundtrack	Bitter soundtrack	Toffee	0–100 rating (sweet, bitter, salt, sour)	No significant difference
Reinoso Carvalho et al. (2016) [9]	Hearing	Extrinsic	Sweet soundtrack	Bitter soundtrack	Belgian beer	1–7 rating sweetness	20%
Reinoso Carvalho et al. (2016) [9]	Hearing	Extrinsic	Sweet soundtrack	Sour soundtrack	Belgian beer	1–7 rating sweetness	20%
Reinoso Carvalho et al. (2017) [22]	Hearing	Extrinsic	Legato soundtrack	Staccato soundtrack	Dark chocolate	1–7 rating sweetness	11%
Wang and Spence, (2016) [23]	Hearing	Extrinsic	Consonant soundtrack	Dissonant soundtrack	Fruit juice (apple, orange, grapefruit)	1–10 rating (sour–sweet)	19%
Wang and Spence (2017) [24]	Hearing	Extrinsic	Consonant soundtrack	Dissonant soundtrack	Fruit juice (apple, orange, grapefruit)	0–10 rating (sour–sweet)	17%
Wang and Spence, (2017) [25]	Hearing	Extrinsic	Sweet soundtrack	Sour soundtrack	Off-dry white wine	0–10 rating sweetness	19%
Wang et al. (2019) [26]	Hearing	Extrinsic	Sweet soundtrack	Bitter soundtrack	Apple elderflower juice	1–9 rating sweetness	8%
Carvalho and Spence (2019) [27]	Sight	Extrinsic	Pink coffee cup	White coffee cup	Espresso	0–10 rating (sweetness)	30%

Study	Sense	Intrinsic or Extrinsic	Sweet Enhancing Stimuli	Control/Comparison Stimuli	Taste Stimuli	Scale	% Difference
Clydesdale et al. (1992) [28]	Sight	Intrinsic	More red colouring	Less red colouring	Dry beverage base and sugar solution	1–7 rating sweetness	14%
Fairhurst et al. (2015) [29]	Sight	Both	Round plate and round food presentation	Angular plate and angular food presentation	Beetroot salad	0–10 rating sweetness	17%
Frank et al. (1989) [30]	Sight	Intrinsic	Red colouring	No colour	Sucrose solution	Rating sweetness	No effect
Hidaka and Shimoda (2014) [31]	Sight	Intrinsic	Pink solution	No colouring	Sucrose solution 4% and 6%	10 cm visual analogue scale (VAS) less–sweeter	40%
Johnson and Clydesdale (1982) [32]	Sight	Intrinsic	Darker red coloured solution	Lighter red reference solution	Sucrose solutions 2.7–5.3%	Magnitude estimation sweetness	2–10%
Lavin and Lawless (1998) [33]	Sight	Intrinsic	Darker red solution	Lighter red solution	Fruit beverage + aspartame to 9% sucrose level	1–9 category scale sweetness	10%
Lavin and Lawless (1998) [33]	Sight	Intrinsic	Lighter green solution	Darker green solution	Fruit beverage + aspartame to 9% sucrose level	1–9 category scale sweetness	8%
Maga (1974) [34]	Sight	Intrinsic	Red colouring	Green, yellow, uncoloured solutions	Sucrose solution	Recognition threshold	No effect
Pangborn and Hansen (1963) [35]	Sight	Intrinsic	Red solution	Green, yellow, uncoloured solutions	Pear nectar	Rating sweetness	No effect
Pangborn et al. (1963) [36]	Sight	Intrinsic	Pink colouring	Yellow, brown, light red, dark red colouring	White wine	Rating sweetness	Rose sweetest

Study	Sense	Intrinsic or Extrinsic	Sweet Enhancing Stimuli	Control/Comparison Stimuli	Taste Stimuli	Scale	% Difference
Pangborn (1960) [37]	Sight	Intrinsic	Red colouring	Green, yellow, uncoloured solutions	Sucrose solution	2-AFC (alternative forced choice) which one sweeter	No effect
Pangborn (1960) [37]	Sight	Intrinsic	Red colouring	Green, yellow, uncoloured solutions	Pear nectar	2-AFC which one sweeter	No effect
Piqueras–Fiszman et al. (2012) [8]	Sight	Extrinsic	White plate	Black plate	Strawberry mousse	10 cm sweetness scale	15%
Stewart and Goss (2013) [38]	Sight	Extrinsic	White plate	Black plate	Cheesecake	10 cm sweetness scale	28%
Wang and Spence (2017) [24]	Sight	Extrinsic	Image of happy child	Image of sad child	Fruit juice (apple, orange, grapefruit)	0–10 rating (sour–sweet)	20%
Wang et al. (2017) [39]	Sight	Intrinsic	Round shape	Angular shape	Dark chocolate	1–9 rating expected sweetness	30%
Dalton et al. (2000) [40]	Smell	Extrinsic (Orthonasal)	Benzaldehyde odour (cherry almond aroma)	No odour	Saccharin solution	Threshold test	29% increase in benzaldehyde threshold in benz + saccharin condition
Delwiche and Heffelfinger (2005) [41]	Smell	Intrinsic (Retronasal)	Pineapple odour, high concentration	Pineapple odour, lower concentration	Aspartame/acesulfame potassium solution	2-AFC threshold detection	Additive taste-odour
Frank and Byram (1988) [42]	Smell	Intrinsic (Retronasal)	Strawberry odour	No odour	Sweetened whipped cream	0–20 rating sweetness	13% at 0.6 M and 1.2 M; 40% at 0.25 M
Frank et al., 1989 [30]	Smell	Intrinsic (Retronasal)	Strawberry odour	No odour	Sucrose solution	0–20 rating sweetness	~18% at 0.3 M, 7% at 0.5 M concentration

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Study	Sense	Intrinsic or Extrinsic	Sweet Enhancing Stimuli	Control/Comparison Stimuli	Taste Stimuli	Scale	% Difference
Schifferstein and Verlegh (1996) [43]	Smell	Intrinsic (Retronasal)	Strawberry odour	No odour	Sucrose solution	150 mm Sweetness scale	25%
Wang et al. (2019) [26]	Smell	Intrinsic	Pomegranate aroma	No added aroma	Apple elderflower juice	1–9 rating sweetness	5%
Biggs et al. (2016) [44]	Touch	Extrinsic	Rough plate	Smooth plate	Biscuits	How did the biscuits taste?	Biscuits in smooth plate 3 times more likely to be rated as sweet compared to those in rough plate
van Rompay et al. (2016) [45]	Touch	Extrinsic	Rounded cup surface pattern	Angular cup surface pattern	Hot coffee and chocolate	1–7 rating sweetness	20%
Wang and Spence (2018) [36]	Touch	Extrinsic	Velvet swatch	Sandpaper swatch	Off-dry white wine (10 g/L)	1–9 rating sweetness	13%
Wang and Spence (2018) [46]	Touch	Extrinsic	Velvet swatch	Sandpaper swatch	Fortified red dessert wine (110 g/L)	1–7 rating sweetness	14%

3. A Neuroscientific Perspective on Sensory Interactions

3.1. The Role of Multisensory Flavour Perception

When it comes to rationalising multisensory integration, Gibson [47] proposed an ecological model whereby information about an object is processed and interpreted via different sensory channels, as part of an active process to acquire information about the environment (see Reference [1] for a review). Flavour perception, then, can be considered as a system that controls ingestion, with the goal of picking up all available information about the food that is about to enter the body in order to secure an adequate supply of nutrients and avoid poisons [48]. Moreover, this process can be considered in multiple stages: first, there is the pre-ingestion period when food is identified and expectations are formed—this is probably most naturally gathered via visual information, together with some degree of tactile (e.g., weight, surface texture, hardness), olfactory, and auditory information (e.g., sizzling, fizzing, bubbling). Then, there is the actual eating/mastication period where additional properties of the food—such as its taste, retronasal aroma, texture, temperature and piquancy—are detected by various taste and oral-somatosensory receptors. These receptors serve to detect nutrients and poisons in the food [49][50]. At the same time, hedonic judgments are made continuously during ingestion as a way of motivating and curtailing ingestion (e.g., [51]). Finally, learned associations are formed between different sensory stimuli as a result of the eating process (e.g., many red-coloured fruits are ripe and sweet [52]).

Just as the tactile system combines disparate information from various parts of the body and various different classes of receptors to register invariant stimuli, the proposed flavour system combines information from all the senses in order to form flavour percepts that ultimately optimise nutrient intake. Viewed from this perspective, extrinsic information such as

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packaging colour or background sound can act to provide extra information about the food that one is about to taste or is currently tasting. According to Bayesian decision theory, the brain uses prior knowledge about what sensory signals go together—whether inborn or explicitly learned—to integrate appropriate sensory stimuli with the goal of maximising the reliability of perceived information [53][54][55] and, presumably, to reduce cognitive load by combining disparate sensory cues into a single object. Cross-modal correspondences involving sweetness (such as with round shapes or consonant harmonies), could act as a conduit (i.e., in the form of Bayesian priors) to help the brain interpret multisensory cues in order to help form taste/flavour evaluations.

3.2. Evidence of Multisensory Flavour Perception in the Brain

In humans, taste is first projected from the tongue and oral cavity to the primary taste cortex in an area of the anterior insula and frontal operculum (see References [56][57] for reviews), along with oral texture and temperature [58][59].

4. A Framework for How Intrinsic and Extrinsic Factors Influence Multisensory Flavour Perception

4.1. Differences between Exteroceptive and Interoceptive Senses

When thinking about the senses and their role in multisensory flavour perception, it can be helpful to distinguish between two categories: the exteroceptive sense of vision, audition, and orthonasal olfaction are typically stimulated prior to (and sometimes during) the consumption of food, and the interoceptive senses (retronasal olfaction, oral-somatosensation and gustation) are those that are stimulated during eating [60]. In the latter case, the relevant senses are taste, retronasal smell, oral-somatosensation and the sounds associated with the consumption of food. Different brain mechanisms may be involved in these two cases. Small et al. [61] found different and overlapping neurological representations of anticipatory and consummatory phases of eating; specifically, the amygdala and mediodorsal thalamus respond preferentially to odours associated with a nutritive drink, whereas the left insula/operculum responds preferentially to the consumption of the drink itself. The right insula/operculum and left OFC responded preferentially to both anticipatory and consumptive phases. Overall, it would seem likely that the multisensory integration of interoceptive flavour cues is more automatic than the combination of cues that is involved in interpreting exteroceptive food-related signals [1][62][63].

One of the most important means by which exteroceptive cues influence food perception relates to expectancy effects [64][65][66][67]. That is, visual appearance cues, orthonasal olfactory cues, and distal food sounds can all set up powerful expectations regarding the food that someone is about to eat. When the food or drink is then evaluated, assimilation may occur if there is only a small discrepancy between what was expected and what was provided. However, if the discrepancy between expectations and the actual interoceptive information is too large, then contrast may occur instead. Human neuroimaging and animal electrophysiology has shown that expectations can modulate sensory processing at both early and late stages, and the response modulation can be either dampened or enhanced (see References [68][69][70] for reviews).

Another example of differences between interoceptive and exteroceptive senses come from Koza et al. [71]. These researchers demonstrated that colour had a qualitatively different effect on the perception of orthonasally (interoceptive) versus retronasally (exteroceptive) presented odours associated with a commercial fruit-flavoured water drink (see also References [72][73]). In particular, they found that colouring the solutions red led to odour enhancement in those participants who sniffed the odour orthonasally, while leading to a reduction in perceived odour intensity when it was presented retronasally. The authors suggested that this surprising result may be accounted for by the fact that it may be more important for us to correctly evaluate foods once they have entered our mouths, since that is when they pose a greater risk of poisoning. By contrast, the threat of poisoning from foodstuffs located outside the mouth is less severe. Alternatively, however, it may well be that people simply attend more to the stimuli within their bodies as compared to those stimuli that are situated externally [55], and that this influence biased the pattern of sensory dominance that was reported.

Given the above considerations, rather than a food-intrinsic versus food-extrinsic divide, it may be more appropriate, with neuroscience and physiology in mind, to divide sensory cues depending on where it is referred. In other words, the key question to consider here is, is the sensory stimulus localised (or perceived to be) coming from within or outside the mouth?

4.2. Oral Referral

The importance of the oral cavity can be seen through the observation that flavours appear to originate from the oral cavity, even if olfactory stimuli are detected in the nose (e.g., [74][75][76], see Reference [77] for a review). In addition, the

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phenomenon of oral referral appears to go beyond merely changing the perceived location of olfactory stimuli; in fact, they are combined with taste information from the tongue to form integrated flavour percepts that cannot be attended to separately [74][78]. Notably, people find it difficult to attend selectively to olfactory stimuli after the stimuli have been localised in the mouth [78][79]. The loss of the source of olfactory information is most likely a result of gustatory attention capture (according to Reference [77]), where the most intense stimulus (normally taste) directs one's attention to the spatial location where that stimulus comes from. This is supported by studies indicating that the degree of oral referral is proportional to the intensity of the tastants, and inversely proportional to the intensity of olfactory stimuli [76].

Intriguingly, the occurrence of oral referral also seems to be related to the degree of congruency between the oral and taste stimuli. Lim and Johnson [80] demonstrated that, when participants were introduced to a simultaneous retronasal odour (soy sauce, vanilla) and a taste solution (sweet, salty, water), they rated the odours as coming from the mouth significantly more often when the odour–taste combination was congruent (vanilla–sweet, soy sauce–salty) than when the solution was neutral or when the combination was incongruent. Further studies conducted with solid gelatine disks instead of liquid solutions [81], and with more ecologically valid stimulus combinations (citral aroma with sweet or sour tastants, coffee aroma with sweet or bitter tastants) revealed similar results where oral referral was enhanced proportional to the degree of self-reported smell–taste congruency [82]. In addition, more recent research supports the hypothesis that retronasal enhancement of odour by taste is dictated by the nutritive value of the tastants in addition to odour–taste congruency; sweet, salt, and umami tastes—which signal the presence of elements essential for survival—presented evidence of enhancing retronasal odour, but no such effect was seen for sour or bitter tastes [83]. In the context of sweetness perception, then, it certainly seems that multisensory cues localised in the mouth (such as food-intrinsic aroma or textural cues) would be more effective in enhancing sweetness perception than those cues localised elsewhere.

5. Combining Intrinsic and Extrinsic Influences

There has been relatively little research on the interaction between food-intrinsic and food-extrinsic factors. The available cognitive neuroscience research suggests that the biggest impact on our experiences and behaviours occur when several sensory attributes are changed at once, and when they complement one another [60]. This is precisely the sort of situation in which one might expect to see an additive response (both in the brain and in behaviour), a response that is far bigger than that which can be achieved by manipulating a single sense individually at a time [84][85].

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