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Sensory influences on food intake control: moving beyond palatability*

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Summary

The sensory experience of eating is an important determinant of food intake control, often attributed to the positive hedonic response associated with certain sensory cues. However, palatability is just one aspect of the sensory experience. Sensory cues based on a food's sight, smell, taste and texture are operational before, during and after an eating event. The focus of this review is to look beyond palatability and highlight recent advances in our understanding of how certain sensory characteristics can be used to promote better energy intake control. We consider the role of visual and odour cues in identifying food in the near environment, guiding food choice and memory for eating, and highlight the ways in which tastes and textures influence meal size and the development of satiety after consumption. Considering sensory characteristics as a functional feature of the foods and beverages we consume provides the opportunity for research to identify how sensory enhancements might be combined with energy reduction in otherwise palatable foods to optimize short-term energy intake regulation in the current food environment. Moving forward, the challenge for sensory nutritional science will be to assess the longer-term impact of these principles on weight management.

Keywords: Food intake, palatability, sensory cues, texture.

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Introduction: moving beyond palatability

The sensory properties of foods and beverages are operational before, during and after an eating event. They direct us towards a food source, guide preferences, portion selection and the experience of fullness after consumption, as well as facilitating dietary learning. There has been a growth in our understanding of the important influence of food's sensory characteristics to the control of energy intake within and across meals, and for the most part palatability has been at the centre of this (1). The view that sensory cues present at the time of eating, such as the sight, smell and taste of a food, can be used to promote overconsumption when they enhance rated palatability is well established, after numerous laboratory studies have demonstrated that people tend to eat more of foods they rate as most palatable (1). Food palatability is defined as the positive hedonic evaluation of food's sensory characteristics (2), which reflects previously learned knowledge that a food's sensory quality is nutritional and safe to eat (3). However, palatability is not a static feature of a food (2), and important concepts such as sensory specific satiety (4) and alliesthesia (5) identify how changes in meal palatability, in response to sensory monotony and metabolic need state respectively, can influence food intake.

It is important, however, to consider the sensory experience of eating beyond what it means for palatability, because people do not *always* eat in the way palatability would predict. For example, a person may rate chocolate as more palatable than a tuna sandwich, but chose to eat the savoury sandwich over the sweet chocolate for lunch because it is more 'appropriate' in a meal context, although both provide necessary calories. Moreover, the ability of a food to suppress appetite post-consumption depends on the oro-sensory experience of eating (6), but the foods rated palatability is less important (1,7). This may reflect inconsistencies in the use of traditional rating scale measures of palatability, which rely on personal introspection and interpretation. Yet more often than not, people eat the food they like (assuming they are affordable and available), meaning that factors other than palatability might explain variations in eating behaviours. While palatability is undoubtedly an important driver of food selection and intake, it is just one aspect of the sensory experience. The current review takes the discussion on sensory influences on food intake beyond their influence on liking and palatability, highlighting recent advances in our understanding of how sensory experience of eating, from a food's visual appraisal, smell, taste and texture, can influence eating behaviour and energy intake over the short term. Considering how the different sensory characteristics of the foods and beverages we consume influence eating behaviour can inform the development of new foods and ways of eating that could be utilized to promote reduced energy intake in the current palatable food environment.

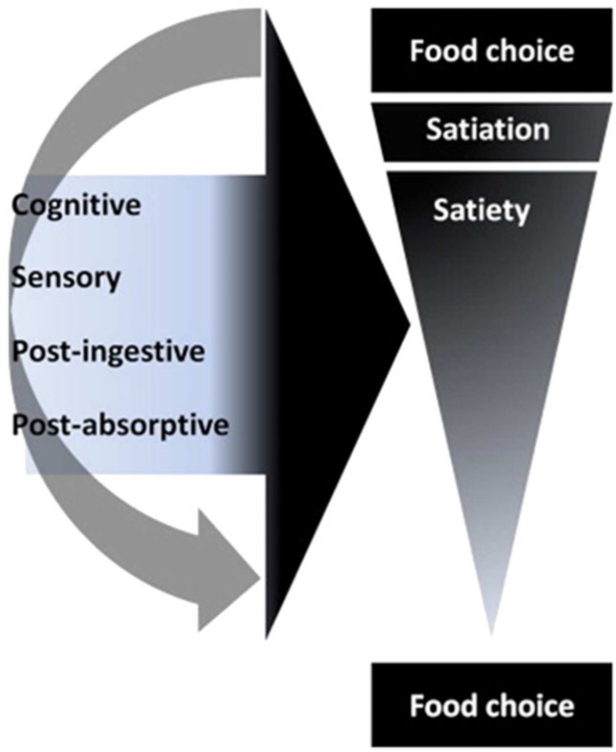

Figure 1 A modified satiety cascade framework, from Chambers, McCrickerd and Yeomans (8), outlining pre-ingestive and post-ingestive influences on the short-term regulation of food intake.

Sensory perception and the control of food intake

Figure 1 provides a schematic of the pre-ingestive and post-ingestive signals known to influence some of the key behavioural aspects of energy intake regulation, adapted by Chambers *et al.* (8) from the original Satiety Cascade framework (9). These behaviours include food choice, how much we consume within a meal (satiation) and the suppression of hunger and future eating in the time after that meal (satiety). Although satiation and satiety are often studied separately, they are underpinned by an overlapping cascade of responses, triggered by the earlier cognitive and sensory appraisal of a food's quality and quantity and the later post-ingestive and post-absorptive physiological signals generated by ingestion and the subsequent digestion of nutrients (9). These signals are combined and fed back through the peripheral nervous system and a number of brain centres, including areas associated with homeostasis, but also learning, reward, memory and attention (10,11), which together (mediated by longer-term metabolic signals) generate the experience of satiation and satiety.

This framework predicts that the satiating effect of a particular food is highly dependent on the early experience of consumption. Cecil, French and Read (6) demonstrated this nicely, showing that a previously satiating 425 g (400 kcal) portion of soup was experienced as progressively less satiating as parts of the eating experience were removed, such that the soup was most satiating when consumed orally with the belief that it was food, and least when infused into the stomach with no oro-sensory exposure and the belief that it was water. The initial experience of eating is important because animals (including humans) learn to eat in response to sensory cues, by forming associations between the early experience of a food's sensory characteristic and the post-ingestive effects of nutrient delivery. Sensory characteristics that consistently cue nutrient delivery acquire meaning and can be used to predict the consequences of consumption (12). This learned integration of pre-ingestive and-post ingestive signals can be expressed as increased liking for nutrient-rich foods and explicit beliefs about a food's potential satieting power (13), which in turn modify food selection and intake. Cephalic phase responses form part of the rapid conditioned physiological response to food-related stimuli, such as salivation (14), gastric acid secretion (15) and the release of some gastrointestinal hormones (16). These responses are triggered upon the sight, smell and taste of a food, to optimize nutrient processing throughout the gastrointestinal tract (15). This indicates that sensory signals present before and during consumption play a functional role in optimizing energy intake regulation, beyond palatability, by informing the perceptual and physiological response to nutrient selection and ingestion.

The following sections consider the sensory experience of consumption, from the moment a food is seen until it is consumed and swallowed. We consolidate recent evidence from studies of visual, odour, taste and texture cues on short-term food intake, going beyond the traditional focus on hedonics to explore how sensory signals generated by the experience of eating have a functional role on food selection, energy intake within a meal and the development of satiety post-meal.

Visual cues

Visual cues offer the first form of sensory interaction with a food prior to its consumption. The sight of a food in the near proximity is enough to trigger meal initiation (17), and food producers carefully consider how the appearance of their products can maximize appeal to the potential consumer. Simply splitting foods like biscuits and chocolate bars so they are viewed as smaller more numerous pieces appears to reduce intake of that food (18,19) without changing pleasantness (20). This 'unit bias' might reflect an increase in the perceived amount of food when it is presented in many small parts (21), or simply a slower eating rate. In contrast, segmenting a food into multiple smaller units can promote intake if this increases perceived sensory variety (22). The size of dishware used is another visual cue proposed to influence meal size, with evidence indicating that some adults and children select and consume larger portions when provided with larger plates, bowls, cups or containers, although this is not a consistent effect (23).

Once consumption is underway, humans continue to rely on visual information to determine meal size. Wansink *et al.* (24) found that covertly re-filling a soup bowl during consumption led participants to eat 73% more soup than those whose bowl was not slowly refilled as they ate. Despite this large difference in intake, participants felt equally full and believed that they had consumed a similar amount of soup, presumably one conforming to the amount they *perceived* leaving the bowl. This highlights how visual heuristics such as 'plate cleaning' and portion cues can direct food intake and override physiological feedback during consumption. For example, people tend to consume more when a food is served in larger compared with smaller portions (24–27). Interestingly, this still happens when visual cues during consumption are removed with a blindfold. Burger *et al.* (28) found that the brief visual assessment of a large vs. small-portion size before blindfolding was enough to prompt participants to consume more from the large-portion by unconsciously increased bite size (but not bite frequency). In this instance, the initial portion size acts as a visual reference for what is an appropriate amount to eat (29), promoting a change in the microstructure of eating that favours increased consumption in both adults and children (28,30–32). This suggests that reducing the predetermined serving size of foods and beverages could curtail energy intake.

So how much we eat can depend in part on how much we see to start with. However, people do not always passively overconsume in response to visual portion cues (33). Some elements of food selection are far more active and based on previous experience. Researchers have demonstrated that aspects of a food's appearance are used to evaluate how filling a food will be before it is consumed (34). For example, brown bread was judged to be more satiating than white bread (35). Researchers have begun to quantify these beliefs (36), finding that satiety expectations are activated upon visual appraisal of a food or meal, with cues such as perceived volume and variety driving these estimations (37,38), particularly when foods are less familiar (39,40). Importantly, these beliefs affect portion decisions and energy intake as people tend to choose and consume larger portions of foods that are expected to be less satiating (41), independent of how much it is liked (42).

Beyond meal size, the visual appraisal of foods can also influence the development of satiety in the time after consumption through memory for recent eating. Using a similar re-filling soup bowl as the one previously described by Wansink *et al.*, Brunstrom *et al.* (43) systematically varied the *perceived* (300 mL vs. 500 mL) and *actual* (300 mL vs. 500 mL) intake by covertly manipulating how much soup was added and removed from the bowl during the meal. They found that people who had seen the larger portion remembered eating more and consistently felt less hungry regardless of the fixed portion they had actually eaten (300 or 500 mL). This appetite effect was strongest at 120 and 180 min after consumption, indicating that beyond a certain time, the experience of satiety was influenced more by what the person saw and remembered eating, and less by what they actually ate. Cassady, Considine and Mattes (44) support this, reporting that identical cherry-flavoured test products suppressed rated appetite and test meal intake 4 h later and even slowed gastrointestinal transit time when participants believed (incorrectly) that they would solidify in their stomach. In reality, all the cherry products were designed to be liquid in the stomach, highlighting how a person's perception of an eating event can shape the actual satiating effect of the nutrients consumed over time, modifying not only the experience of satiety but also gastrointestinal responses.

Overall, visual food cues are an important determinant of food selection and intake, beyond simply initiating a meal. During consumption, visual cues are often relied on to inform when to stop eating, and cues that nudge us towards serving and eating larger portions have been associated with overconsumption in what appears to be a passive way. But the visual appraisal of a food can also evoke beliefs and expectations about the satiating properties of that food, which can be used to guide decisions about what we put on our plate and subsequently eat, with new evidence indicating that memories for these cues have the potential to modify the experience of satiety in the time between meals.

Odours

Food odours are an important sensory signal and an integral part of human flavour perception, shaping the way tastes and textures are experienced (45). Food odours signal the near presence of edible (and inedible) foods, even before a food can be identified visually (46). Many food establishments use the tempting aromas of their products to entice in potential customers (47). Laboratory evidence suggests that cuing a person with very pleasant food odours, such as the smell of pizza or warm cookies, can stimulate salivation (48–50), promote appetite and prospective consumption and even increase food intake in particularly sensitive individuals, depending on their body mass index (49,51,52), level of dietary restraint (51,53–55) and reported impulsivity (56).

Two food-related odours of equivalent pleasantness and intensity do not always have a general stimulatory effect on appetite and food choice (57). For example, Ramaekers *et al.* (58) found that well-liked ambient food odours (bread, tomato soup, savoury meats, chocolate and banana) stimulated appetite for and selection of the cued food specifically, but not the other food items. Similarly, other researchers have reported that sub-threshold exposure to fruit odours prior to a meal led participants to choose more fruit and vegetable-based foods at a subsequent meal (59,60). This suggests that odours can direct food choice towards the food that is signalled by the odour specifically. One possibility is that food odours, whether perceived or not, not only direct attention towards these food sources, perhaps through priming implicit memories, but also could arouse anticipation of nutrients or the energy associated with consumption. For instance, recent evidence reported that a low-protein diet modulated neural responses in brain areas associated with reward in response to savoury food odours (61). However, evidence for a strong link between odour cues, need state and energy selection remains poor. Zoon *et al.* (62) found that exposure to ambient odours that signalled high or low energy-dense sweet and savoury foods had no effect on the consumption of these foods, and this did not vary with hunger state. Moreover, very pleasant non-food odours have also been shown to reduce appetite (58), so although ambient odours may direct us towards food sources, the extent to which these odours are utilized to discriminate foods based on their nutrients and possible post-ingestive consequences remains unclear.

A distinction can be made between odours acting orthonasally (perceived to originate from the external environment) and retro-nasally (perceived to originate from the mouth). Once a food enters the mouth, aroma released directly from the food matrix during mastication increases the perceived intensity of a food's flavour (63). The profile of retro-nasal aroma release depends on the physical structure of the food being consumed, such as texture and food form, as well as characteristics of the individual consumer, such as bite size, eating rate and chewing efficiency (64–68). Using a combination of olfactometry and atmospheric pressure chemical ionization-mass spectrometry, researchers have attempted to isolate, manipulate and measure the effect of retro-nasal aroma release on appetite and meal size by administering specific concentrations of odour stimuli to the oral cavity prior to and during consumption, independent of the food being consumed. These methods have shown that more intense but similarly pleasant retro-nasal aroma release profiles could lead to variations in bite size (69). Moreover, enhancing the typically weak retro-nasal aroma release associated with consumption of a liquid beverage to mimic the slower-release characteristics of a soft-solid food increased the perception of how filling the beverage was but failed to alter *ad-libitum* intake (70). A similar suppression of rated appetite was achieved by increasing the perceived complexity of a beverage's strawberry aroma while holding flavour intensity and pleasantness constant, although again, intake was unaffected (71). Yet increasing retro-nasal aroma stimulation of a tomato soup aroma did lead to a 9% reduction in soup intake when bite size and eating rate was standardized (72), suggesting variations in way in which we eat (e.g. food selection, bite size and eating rate) are enough to mask what appears to be a relatively small effect of retro-nasal aroma release on meal size.

To our knowledge, no published research has directly tested whether the impact of a food's aroma on appetite and intake extends beyond one meal to the next. Based on the evidence outlined earlier, however, it seems likely that the functional role for odour in short-term regulation of food intake lies in the detection of foods and direction of choice, and less in the development and maintenance of satiation and satiety over time. Retro-nasal odour exposure appears to have a small and inconsistent effect on satiation and *ad-libitum* food intake, whereas ambient odours could be used to create sensory specific appetites for healthier foods.

Taste

Vision and olfaction can both be used to identify edible foods in the near environment, but taste is a proximal sense that requires direct contact with taste stimuli on the tongue to determine the nutritional quality of ingested food (12,73,74). The basic tastes (sweet, salty, bitter, sour and umami) are believed to signal the nutrient-rich food, with sweet taste indicating carbohydrates, particularly monosaccharides and disaccharides and salty and savoury tastes associated with electrolytes and protein (75), whereas sour and bitter taste may signal unripe fruits or foods that could be harmful when ingested. Infants show an early preference for sweet and salty tastes and an aversion to bitter and sour (76). Although both adults and children can learn to like bitter and sour-tasting foods (77), as adults, the majority of our energy intake still comes from food sources that can be described as sweet or salty (>85%), while little energy (<15%) comes from foods described as bitter or sour (78), highlighting the close association between our general taste preferences, food choice and intake. Indeed, small changes in the taste of a food can have relatively large effects on appetite and food intake when they affect palatability (79). For example, people eat more of a previously bland food if it is made to taste more palatable by adding sweetness, salt or various herbs and spices (1). Unsurprisingly, this strongly depends on an individual's personal preferences for these tastes: people who reported a greater liking for sweet foods compared with savoury ate more of a sweet rice compared with a savoury version (80). The opposite was true for those who reported a greater liking for savoury foods, while people who had no clear preference consumed a similar amount of both dishes.

The optimum or 'preferred' level of a taste varies widely from person to person and is likely due to dietary experience and the prevalence of that taste in a person's food environment. For example, an individual's taste preference for salty foods can be shifted up or down following an extended period of salt use or depletion (81,82). Unsurprisingly, people tend to eat more of food containing their most preferred concentration of a taste (83,84). The relationship between taste intensity and palatability in response to varying taste concentrations is represented by a psycho-hedonic curve (Fig. 2). Using taste intensities established by this relationship, Yeomans (2) measured intake of pasta with sauce containing each participant's most preferred concentration of salt alongside two other concentrations of neutral palatability, one above and one below their most preferred salt level. As predicted, participants consistently ate most of the meal with the preferred salt taste. However, palatability did not predict intake of the other two meals, as the high-salt soup was eaten less and experienced as more satiating than the low-salt version that was similarly neutral in palatability.

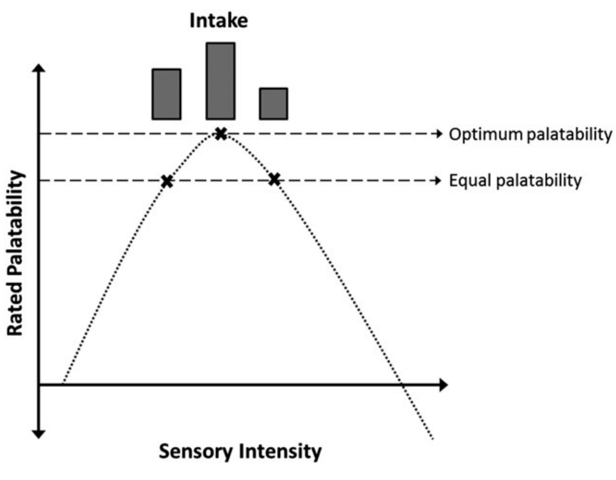

Figure 2 An illustration of the reported relationship between sensory intensity, rated palatability and food intake. As sensory intensity increases (e.g. taste intensity as a function of tastant concentration), palatability also increases up to an optimum, after which further increases in intensity become less palatable. This inverted u-shaped relationship is known as a Wundt curve.

Similar studies have also documented what appears as an increase in satiation in response to stronger-tasting foods (85–87), although not always (88,89), suggesting that although a food's initial palatability can increase food intake, perceived taste intensity independently acts to curtail an eating event (Fig. 2). This was confirmed in recent work by Bolhuis *et al.*, who reported that participants consistently ate ≈ 9% less of a tomato soup with a high-salt compared with low-salt intensity, despite these soups being similarly palatable (90,91). This effect was only diminished when participants report being hungry and when meal variety was low (92).

It is plausible that taste intensity suppresses intake of palatable foods by modifying within-meal changes in palatability (i.e. sensory-specific satiety). Vickers *et al.* (89) reported that the reduction in liking over the course of consumption was steeper for strong vs. weak-tasting tea. However, this was not associated with an overall reduction in intake in that study, and others have reported equal reductions in palatability for both high and low taste intensity meals (86,90,91). This suggests that intense taste promotes meal termination in a different way to sensory-specific satiety. One possibility is that reduced intake of stronger tasting but palatable food represents a form of sensory self-regulation, independent of changes in palatability, whereby a person manages the more intense but still enjoyable sensory experience by reducing intake. If so, this might be seen in changes to a reduction of eating rate and/or bite size as a means of moderating sensory stimulation. But while initial evidence from Bolhuis *et al.* (90) suggests that bite size tends to be smaller for a strong-tasting food, this effect did not explain reduced intake compared with a weaker-tasting meal, which remained even when bite size is standardized. Thus, whether taste intensity influences intake through changing the microstructure of eating requires further examination.

An alternative possibility is that stronger tastes curtail intake if a person associates this sensory experience with the presence of nutrients in food, and adjusts their intake accordingly. A role for umami taste in appetite regulation is particularly interesting in this regard, because of its suggested role as a signal for protein in the diet (93,94). Umami, described as 'savoury deliciousness', does appear to be a nutritionally relevant sensory cue. For instance, greater sensitivity to umami taste is linked to increased liking for protein-rich foods (95), and protein deprivation can lead to increased preference and intake for savoury foods (61,96). Monosodium glutamate (MSG) can be added to a food to increase savoury umami taste and increase palatability, but the predicted increase in consumption of MSG-enhanced vs. bland foods is not consistent (97). One explanation is that an increase in palatability is offset by an increase in taste intensity acting to suppress intake, because a strong umami taste might signal the imminent arrival of nutrients. In support of umami as a protein signal, researchers have suggested umami taste could be used to moderate the experience of satiation and satiety when paired with protein-rich foods (98). Masic and Yeomans investigated the satiating power of equicaloric protein-rich vs. carbohydrate-rich carrot soups, alongside a low-energy control, with and without a strong umami taste of MSG. Adding MSG increased the initial palatability of these otherwise bland carrot soups, but post-consumption participants tended to feel fuller and compensate more at later test meal for the nutrients in the MSG-enhanced protein-rich soup, compared with the bland high-protein version. On the other hand, adding MSG to the equi-caloric carbohydrate rich soup or a low-energy control soup had no impact on satiety responses (99,100). Similar findings were reported for a combination of inosine 5′-monophosphate alongside MSG in a protein-rich soup (101). Other researchers using lower proportions of protein in their test foods have reported minimal to no effect of umami taste on protein-based appetite suppression and future intake (98,102–104). Thus, more research is required to assess whether the satiating effect of umami depends on congruent protein delivery to determine the relevant quantities of protein and umami taste needed for this interaction.

Another way taste cues can influence energy intake is through their application to reduced-energy foods. The effect of low-calorie sweeteners on appetite and energy intake has received research attention because of their ability to deliver sweet taste while reducing the energy provided by sugar in many sweet foods and beverages (either partially or fully). Findings from a number of reviews and recent comprehensive meta-analyses of short-term and long-term interventions (up to 40 months) support the hypothesis that consuming artificially sweetened lower-calorie foods and beverages in place of equally palatable full-energy versions can reduce overall energy intake and promote weight maintenance and even weight loss (105–108). This seems primarily because of a lack of full compensation for the calories replaced by sweeteners and because people tend to feel similarly satiated having consumed fewer calories, as long as taste is unaffected. Some researchers have questioned whether regular consumption of low-calorie sweeteners is diluting the strength of sweet taste as a predictive cue for energy in foods, potentially impairing our ability to learn about the satiating effects of foods, and in particular sweet beverages (109,110). In these studies, rodents repeatedly exposed to foods containing artificial sweeteners and fat replacers in the place of calories were less able to adjust their intake in response to similarly tasting but energy-rich foods, and often gained more weight than the rodents that experienced consistent sensory-nutrient pairings in their diet. However, given the complexity of human dietary experience and the lack of compelling evidence linking regular consumption of non-nutritive sweeteners to weight gain, exposure to inconsistent sensory-nutrient relationships in some foods may have limited impact on human eating behaviours (108).

To summarize, when a food enters the mouth, its taste provides vital information about nutrient quality and acceptability. There is a strong link between taste quality and palatability. For instance, adding certain tastes to foods, such as sweetness and saltiness, increases palatability, which in turn drives intake. However, studies have also shown that increasing taste intensity while maintaining a food's palatability can reduce within-meal energy intake by $\approx 9\%$. This enhanced satiation could be an expression of the learned association between taste intensity and the presence of nutrients in food. The ability of taste intensity to modify food intake is likely malleable, shaped by our habitual exposure to taste qualities over time. Beyond meal size, evidence suggests that taste signals, such as umami and sweet taste, might be added to foods to improve the satiating power of the nutrients they predict and to maintain the sensory experience of reduced energy foods and beverages. As our understanding of the taste system improves and new tastes are debated, as is the case for fatty acid taste (111), the need for researchers to consider the functional role of emergent taste qualities in the short-term control of energy intake will only increase. What will have to be considered is the variation between individuals preference for different tastes and taste intensities and the fine line between a strong tasting food being considered palatable or not.

Texture

Texture is the multimodal-sensory characteristic of food described as 'the sensory and functional manifestation of the structural, mechanical and surface properties of foods detected through the senses of vision, hearing, touch and kinesthetics' (112). Food texture is conceptualized through a variety of attributes, such as firmness, crunchiness, smoothness, creaminess and thickness, and like taste, texture is an indicator of food quality and a major determinant of consumer acceptance (112–114). Recent research has highlighted the role food texture plays in moderating energy intake. For instance, we consume foods at different rates depending on their texture. Many solid foods are consumed at rates of <10 g to $100\ \mathrm{g\ min^{-1}}$, whereas liquid beverages are consumed much faster, often over $600\ \mathrm{g\ min^{-1}}$ (115–117). Viscous, chewy and hard foods are consumed more slowly and are consistently ingested in smaller quantities than foods and beverages with softer textural characteristics (118–124). Importantly, these studies report participants feeling equally full after the harder 'slow foods' compared with softer 'fast foods', despite within-meal energy intake reductions of 10–30%. This reduction is independent of reported palatability and occurs with little or no awareness as people eat in response to the textures served, by taking smaller bites and chewing for longer (118,123). Moreover, these data highlight that people tend not to compensate for the reduced meal size later in the day. This is in line with evidence that the reduction of food intake in response to stronger tasting food (≈9%) is comparatively less than that reductions achieved by texture modifications (90), presumably because tastes do not alter oro-sensory exposure time.

In addition to increasing oro-sensory exposure, food textures also guide beliefs about the potential satiating effects of a food or beverage, which can influence meal size through portion decisions. Recent research reports that foods perceived to be chewier and thicker are believed to be more filling (115,125), and adding subtle thick and creamy textural characteristics to a beverage to increase the extent to which it is expected to suppress hunger (126). Interestingly, creamy flavours that do not alter texture are much less effective at guiding beliefs (125,126) and fail to reduce portion selection and intake to the same extent as thick texture cues (127). Again, this can be attributed to textures having a larger impact on oral processing, which aids estimation of the nutrients in a food because increased sensory stimulation can enhance learning about the food's satiating power (128). Once learned, beliefs about the superior satiating power of foods perceived to be thicker and chewier appear to be hard to change (129,130), indicating that these learned relationships may be particularly robust. Indeed, harder, chewier, thicker and creamier foods that are eaten more slowly tend to be nutrient-rich, containing more protein, carbohydrates and fibres than low-viscosity foods and beverages with a higher water content (117). These data suggest that adding harder, chewier and thicker textures to foods and beverages without increasing their energy content could improve food selection and meal size by (i) moderating eating rate and (ii) informing decisions around the type and quantity of food selected and consumed.

Beyond food selection, food texture has been identified as having an important role in the development of satiety and, in particular, the reported superior satiating power of solid vs. liquid calories. Many studies have reported that liquids consumed as beverages fail to suppress appetite and subsequent energy intake to the same extent as semi-solid and solid versions of the same nutrients (44,131–136). These studies manipulated food form while maintaining other features that might impact satiety, such as taste and macronutrient content. Gastrointestinal processing and transit times are generally reduced for liquids (137), meaning that post-ingestive factors likely account for some of the reported weak satiating value of liquids compared with solid foods. However, evidence that the same liquid was more satiating when it was consumed slowly by using a spoon, compared with being drunk from a glass (138), supports the hypothesis that longer oro-sensory exposure time afforded by food textures improves satiety responses to ingested nutrients. This is because liquids that are drunk require little oral processing and fail to elicit sufficient cephalic-phase preparatory responses in the same way as solid foods that require chewing (139,140), and increasing oro-sensory by deliberately processing a food longer in the mouth has been shown to increase the experience of satiety and gastro-intestinal peptide release (141–144). At the cognitive level, it is also possible that solid foods and soups are experienced as more satiating because they are considered to be 'foods' for fullness, whereas beverages consumed in the context of thirst are expected to have a weak impact on satiety, and these beliefs can contribute to weaker satiety responses (145). What is most likely, however, is that a combination of cognitive, oro-sensory and post-ingestive factors explains the satiating effect of solid compared with liquid calories (44).

Evidence that textural cues can modify consumer satiety responses suggests that textures could be used to improve the satiating power of a food. Indeed, relatively subtle within-product differences in viscosity can alter satiating value of a beverage, despite providing a similar gastric challenge (146). Yeomans and Chambers (147) demonstrated that in a beverage context, a covert difference of almost 200 kcal between two low-viscosity beverages (lower energy vs. higher energy), matched for appearance, oro-sensory characteristics, pleasantness and serving size (g), had little impact on satiety responses. On the other hand, when the same beverages were consumed in subtly thicker and creamier textural context, achieved by small additions of thickener, participants felt less hungry and ate significantly less at a later test meal after the higher-energy beverage, but not the lower-energy version. This finding has been replicated on several occasions (8) and by other researchers using different palatable foods (148). Importantly, sensory enhanced satiety was still evident after 10 exposures to the thicker and creamier higher-energy beverages when participants consumed them over a 3-week home-based consumer trial (149), although when exposures were confined to the laboratory, consumers did learn to respond to the higher-energy content beverages independent of the sensory cues (130). These data suggest that the post-ingestive satiating power of nutrients depends on the sensory cues present at the time of consumption and that textures predicting the presence of nutrients can enhance the satiating power of higher-energy beverages. Evidence that these effects can persist after repeated exposure in a real-world setting is promising for the longer-term application of satiety-relevant texture enhancements to foods.

Overall, food texture is a particularly important driver of food intake behaviour that can be utilized to reduce energy intake in the diet. Firstly, modifying food texture to be harder, chewier or more viscous, without the addition of calories or a change in food acceptance, can reduce meal size and improve the satiating power of the nutrients they contain. This occurs fairly passively when consuming foods *ad libitum* as people eat faster and take larger bites from softer foods, often without realizing. Secondly, textural cues have a strong ability to influence consumer beliefs about the potential satiating effects of a food. Such beliefs are robust and can impact food intake through informing portion selection decisions and increasing the extent to which a food is experienced as satiating in the time after consumption. Finally, textural cues are particularly effective at optimizing the post-ingestive satiating value of nutrients contained in these foods when they increase oro-sensory exposure and correctly predict the nutrients being delivered. Together, this suggests that applying satiety-relevant textural cues to energy-containing foods could be one useful strategy to encourage improved appetite control.

Summary

The sensory experience of eating is multifaceted and has a functional role to play in energy intake regulation, beyond simply guiding food choice and hedonic value. In the same way that the sensory exposure to food and food cues is one important factor influencing food choice and the optimum development of satiation and satiety, each component of the sensory experience drives these behavioural responses to food in a number of different but undoubtedly overlapping ways.

Visual food cues help locate foods and can influence consumption in a relatively passive way through triggering portion norms, unit biases and behaviours such as plate cleaning. The sight of a food triggers learned beliefs about its anticipated taste and satiating properties, which influence food selection and intake, and memory for the amount of food consumed helps shape the development of satiety and later food choice. Ambient food odours also have a functional role in energy intake primarily prior to consumption, helping locate food sources and stimulating a desire to eat. Once consumption is underway, however, retro-nasal aroma release seems to have little impact on the amount of food consumed or subsequent satiety post-meal. Instead, the intensity of taste cues can be used to curtail food intake within a meal when they do not have an adverse impact on palatability. Tastes that are representative of nutrients may have a functional role to play in the development of both satiation and satiety. What this reveals is that odour and taste, despite being so perceptually intertwined in the experience of food 'flavour', have quite different independent effects on food selection and intake. However, this is less surprising when we consider how these senses differ: gustation and olfaction are underpinned by different physiological mechanisms and neural circuits. While taste is based on a small class of receptors to detect five basic tastes once food is present in the mouth, olfaction uses many receptors to detect thousands of different smells before and during consumption. In this way, olfaction is set up to detect and identify a wide variety of foods, whereas taste provides a rapid evaluation of a food's quality based on a few important chemicals. Recent evidence suggests that textural modifications may be particularly important in guiding our eating behaviour, which can be used to moderate energy intake. Food texture influences oral processing, which determines how long a food spends in the mouth and in contact with the chemo-sensory systems. This can shape our beliefs about the satiating power of a food and trigger anticipatory physiological responses to nutrient ingestion. The evidence presented in this review suggests that foods with textures that predict nutrients and increase oro-sensory exposure time could reduce energy intake by being selected in smaller portions, being consumed at a slower rate and interact with nutrient processing to enhance the experience of satiety in the time after consumption.

Moving forward with sensory nutritional science

Further research is now required to explore how these findings could be applied in the design of foods and beverages with sensory and nutritional characteristics that optimize energy intake regulation. Sensory signals generated by food could be used to promote better food choices and energy intake regulation by influencing how much we eat, and how we eat it, beyond how much a food is liked. To date, the impact of visual cues, odours, tastes and textures on eating behaviour in the short term has been studied in isolation, but in typical eating situations, these cues will be integrated together and combined with the post-ingestive effect of nutrient ingestion. Future research should consider the relative and combined contribution of the collective sensory experience to evaluate their contribution to appetite control and explore the interaction with nutrient-based post-ingestive effects. Evidence that the sensory characteristics of a food can promote satiation and satiety provides the opportunity for future work to consider extent to which sensory enhancements can be combined with energy reduction in foods to optimize satiation and satiety and reliably reduce energy consumption over the longer term. An important part of this will be achieving such sensory modifications in a range of foods that are accepted by a variety of consumers. But perhaps most importantly, research will need to assess the long-term efficacy of these findings to truly understand how foods' sensory cues could be optimized to make a meaningful contribution to strategies for weight management. This will depend on the mechanisms that underpin these effects, which are multifaceted and require further clarification, but evidence to date suggests these include features of dietary learning and memory, such as consumer expectations, oral processing behaviours and cephalic phase preparatory responses. Throughout all of this, tackling the individual nature of sensory preferences and eating behaviours will be a major challenge. Sensory cues that are tightly coupled to food's rated palatability, such as taste intensity, would need to be personalized to the individual and frequently re-evaluated. The effectiveness of influences less dependent on palatability, such as introducing textures that prolong eating rate and oro-sensory exposure, will rely not only on an individual's existing eating styles but also a clearer understanding of palatability and how it is represented both behaviourally and in the brain. Nevertheless, away from the need for evidence-based support for a functional role for sensory characteristics in the promotion of weight management, the immediate impact of this work from the field of sensory nutritional science should be the clear message that sensory cues present at the time of consumption have nutritional meaning; their influence on short-term energy intake extends beyond the traditional notion of food palatability, acceptance and choice

Conflict of interest statement

The authors declare no conflict of interest.

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