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Sensory influences on food choice and energy intake: recent developments and future directions

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12.1 Introduction: the role of sensory cues in food choice and intake

People select and consume more of their energy from the foods they like, and tend to avoid foods they dislike. Food liking is largely determined by the physical and chemical properties that are sensed by a number of independent and integrated sensory systems. Vision and olfaction are distal senses that are primarily involved in the location of food sources, guiding choice in the anticipation of food intake, and stimulating sensory-specific appetites. The proximal senses of audition, taste, retronasal olfaction, touch (texture), and trigeminal stimulation are activated during food consumption, and form an important connection between what is experienced during the meal (satiation) and the postingestive feeling of satisfaction derived in response to the integrated sensory experience (satiety) (Forde, 2018b). The brain integrates these sensory signals into a single but dynamic sensory perceptual impression that determines liking, and guides food and beverage choice and intake behavior (Forde, 2016).

Food consumption does not occur in a vacuum, and previous research has highlighted that in addition to sensory perception, consumers anticipate the consequences of ingestion in the wider context of their goals, motivations and attitudes toward the role of food in good nutrition and health (Rozin and Vollmecke, 1986). Beyond perception and motivation, consumption norms, meal context, and the perceived appropriateness of the food in the specific consumption context are also considered, such as eating turkey at Thanksgiving/Christmas (Al-Swidi et al., 2014). Although these cognitive top-down effects may impact choice and intake, sensory signals form the biological basis for ingestive behavior and are the focus of the current chapter.

The sensory signals from foods and beverage are operational before, during, and just after eating and drinking (Blundell et al., 2010). Sensory cues occur early before and during consumption before endocrine and visceral changes, and exert most influence on intake to fullness (satiation), with less influence on postingestive experiences of fullness (satiety) (De Graaf et al., 1999). We learn to associate the postingestive

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feelings of fullness and satisfaction with the sensory cues experienced during food intake (Yeomans, 2006). This process of flavor consequence learning means we develop the ability to estimate the postingestive consequences that come from consuming specific foods and drinks and this informs our expectations of fullness and the amount of calories (portion) we choose to consume (i.e., portion size) (Forde et al., 2015). These perceptions guide our daily food choices and appropriate portion size selections, ultimately resulting in habitual meal and dietary patterns that form the basis for healthy or unhealthy eating patterns (Brunstrom, 2007).

A higher palatability (liking) of a certain food leads to an increased likelihood of selection of that food among alternatives within the same category (De Graaf et al., 2005). Food producers optimize their products' sensory appeal to enhance liking to win greater share of the market. Liking has been shown to increase acute intake (Yeomans et al., 2001; Yeomans, 1998), and although this relationship is initially linear, it plateaus and becomes attenuated such that food intake does not continue to increase linearly at high levels of liking (De Graaf et al., 2005). This highlights that in a world dominated by highly palatable foods, the usefulness of palatability in explaining large variations in dietary energy intake in the real world may be somewhat limited, and other aspects of a food's sensory properties are likely to contribute to observed variations in intake.

The current chapter provides an update on what is known about the role of sensory cues in driving choice and intake behavior. We begin by discussing the role of each sense modality in food choice and intake, focusing on odor, taste, and texture. Recent years have seen progress in our understanding of the role of the senses in ingestive behavior and nutrition, beyond their impact on palatability (McCrickerd and Forde, 2016), and extended this to understand dietary patterns of intake within a food environment and population. A perspective on progress has been made in understanding how sensory cues influence our dietary patterns, and offers directions for future application of sensory science in supporting healthy and sustainable diets.

12.2 Impact of food odor on food choice and intake

Odor detection is important for food choice and intake, and plays an important role in the detection of danger, irritation (e.g., smoke, household gas, industrial and/or agricultural pollution), and social interactions (Boesveldt and de Graaf, 2017). There are a wide diversity among odor qualities and combinations, and we integrate this complexity into a single holistic impression such that our primary response to odors is emotional (valence; like vs. dislike). Odor associations are flexible, and may depend on culture and experience, through which odors acquire their meaning and their association with certain foods/objects (Marty et al., 2017). Odors can often acquire their meanings through how they are labeled, and previous research has shown that the hedonic valence of an odor mixture can change from liked to disliked when labeled as either "vomit" or "parmesan cheese" (Herz and von Clef, 2001). This is also seen in brain responses to the same or similar odors that are labeled differently (De Araujo et al., 2005).

Olfaction is a distal sense, and volatile compounds detected remotely can exert an influence on appetite, food choice, and intake through orthonasal *odor* detection ("sniffing" odor) and during consumption via retronasal (*aroma*) perception. Orthonasal *odor* perception provides remote access to information from the food environment through peripheral odor receptors and is mainly involved in the anticipation of consumption, stimulating a desire for specific food choice and intake. Retronasal odor perception is when volatile compounds are released during mastication and after swallowing and combine with a foods' taste and texture information to produce the overall perceived flavor. Orthonasal and retronasal odors are perceived differently and have different responses in the central nervous system, and therefore they also have a different role in eating behavior.

12.2.1 Ambient odors perceived orthonasally; effect on appetite, choice, and intake

Most people recognize that when they are hungry and smell a particular food, it tends to prime you to the pleasure of consuming that food. Early studies that demonstrate the appetizing effect of ambient odors conducted by Fedoroff et al. (1997, 2003) and later studies (Ferriday and Brunstrom, 2008; Ramaekers et al., 2014a) confirmed that specific odors (e.g., pizza or cookies) enhance appetites for odor-cued food. Further studies of sensory-specific appetites showed that specific appetites generalize to some extent to similar foods within the same or similar sensory and nutritional properties. For example, banana odor induces a higher appetite for bananas but also the appetite for sweet tasting foods, whereas it suppresses the appetite for savory tasting foods. By contrast, the savory odor of meat enhances the appetite for meat, increases the appetite for other savory foods, but suppresses the appetite for something sweet (Ramaekers et al., 2014a,b). Sensory-specific appetites also generalize across categories of foods with either a low or high energy density (Proserpio et al., 2017). This aligns with the evidence showing that humans have better spatial memory for odors that signal the presence of higher energy foods, compared to low energy-dense foods (de Vries et al., 2020).

The role of ambient odors on actual food choice and intake is somewhat less clear compared to the effect on sensory-specific appetites. Studies that investigate the effect of food odor on food choice have exposed subjects to low intensities of unattended odors of different sources to compare the impact on subsequent food choice. In one such study, a lemon odor was presented in a waiting room and participants were later asked to choose foods from a menu (Gaillet et al., 2013). Exposure to lemon odor was associated with subjects choosing a starter with vegetables; however, there were not more choices for fruits and vegetables at the main menu and/or dessert. In a follow-up study, subjects were exposed to a pear odor which was associated with a higher frequency of selecting a dessert with fruits, but not with vegetables and/or fruits with starters or main menu (Gaillet-Torrent et al., 2014). This was confirmed in a larger study where over 100 participants were again presented with an unattended pear odor which was associated with a higher frequency of selecting a dessert containing fruit from a buffet style lunch, whereas control subjects were more likely to choose a brownie (Gaillet-Torrent et al., 2014). A subsequent study exposed a group of 45 non-obese children and 29 children with obesity to no-odor, a fruity odor, or a fatty-sweet odor and observed the impact on food choice among children (Marty et al., 2017). Priming children with obesity with a fruit odor led to an increase in subsequent choices for fruit; however, among the normal weight group, odor exposure led to a decrease in choice for specific foods. Extensive follow-up studies on the effect of consciously attended and unattended odors on food choice and intake failed to find an effect of exposure on actual choice (Morquecho-Campos et al., 2020), suggesting these effects are inconsistent and often rely on the specificity of the food odor quality, its perceptual intensity, and the nature of the food choice task.

Taken together these results suggest that the impact of ambient odor exposure on actual food choice and intake is mixed and are likely contingent on many factors. Whereas effects on sensory-specific appetites and food choice are somewhat consistent, there is less evidence to support an effect of odor exposure on food intake. Early studies showed that food cue odor exposure had a larger effect on food choice among restrained eaters rather than unrestrained eaters following (specific) food odor exposure (Fedoroff et al., 1997, 2003). Similarly, subsequent studies have shown small increase in "chocolate rice" intake after being exposed to a chocolate odor, but not after exposure to other odors (Proserpio et al., 2017). A later study observed that women with obesity tended to eat more soup after being exposed to bread odor, than in an "unscented" condition (Proserpio et al., 2019). The potential application is to apply odors to guide choice and stimulate specific appetites, and this could be a cost-effective approach to stimulate and encourage food intake among populations that are vulnerable or at risk of malnutrition. When patients with Alzheimer disease were exposed to ambient meat odors before a lunchtime meal on two occasions, there was a positive effect of the ambient odor exposure on meal consumption in the first, but not the second meal (Sulmont-Rossé et al., 2018). Studies have also tried to stimulate macronutrient specific appetites and link to intake by exposing participants to odors representing various macronutrient sources (carbohydrates, protein, fat) and tastes (sweet, savory), but this has failed to influence subsequent intake (Morquecho-Campos et al., 2019, 2020).

Retronasal aroma release and perception during consumption has a significant impact on flavor perception and consumers appreciation for a food's sensory appeal. When suffering from a cold the retronasal aroma is blocked and people often complain that food has "no taste," highlighting the important role of aroma in flavor perception and hedonic appeal. Similarly, people suffering from anosmia often express lower food enjoyment during consumption than those with normal smell function (Boesveldt and de Graaf, 2017). In this way retronasal aroma perception can play an important role in food liking and can have a positive impact on intake. However, studies have also explored the potential of retronasal aroma perception to influence eating behavior during a meal and stimulate an earlier onset of satiation, thus reducing energy intake (Ruijschop et al., 2008a). Studies have carefully manipulated the delivery of retronasal aromas to independently influence perceived intensity from that released from the consumed food itself. Initial results from these studies suggested that the duration and intensity of retronasal aroma stimulation could influence the onset of satiation, with small effects of retronasal aroma on subjective ratings of appetite or ad libitum food intake (Ruijschop et al., 2008a,b, 2009a,b,c, 2010). The potential application of adding low energy volatile odors to a food to help moderate intake is an attractive proposition, yet the overall effect-size and reproducibility of their impact on intake is disappointing. Later attempts to replicate the effect of odor stimulation on food intake confirm that this is unlikely to be an effective approach to reducing energy consumed in a realistic meal, and that odor stimulation is more likely to influence the initiation of food intake, than its termination at the end of a meal (Boesveldt and de Graaf, 2017).

Whereas ambient odors seem to have a reproducible effect of stimulating sensory-specific appetites, the effects on food choice and intake have been more difficult to replicate, and may depend on a range of individual and food-related conditions. For example, the efficacy of this approach is likely to be influenced by the properties of the person such as age, gender, weight status, degree of restrained eating, acute hunger status, whereas the perceptual conditions, such as the odor duration, intensity, and quality and whether or not it is consciously perceived are all likely to influence choice behavior. The public health nutrition potential of odor stimulation has yet to be fully realized, and it remains unclear whether priming appetites and choice for healthier food items using unattended ambient odor may be used to positively impact eating behavior in a real-life eating situation.

12.2.2 Odor perception and body weight

There has been increased interest in the relationship between odor sensitivity and weight status, with the suggestion that deficits in perceptual acuity may be linked with higher food intake and body weight. A recent systematic review of studies on odor sensitivity and body weight concluded that there is a relationship between impaired olfactory perception and obesity (Peng et al., 2019). For example, studies report olfactory decline among patients with higher BMI, but studies with bariatric patients who received both *Roux-en-Y* gastric bypass and particularly sleeve gastrectomy showed a recovery in olfactory function post-surgery (Peng et al., 2019). Others have shown a negative correlation between olfactory discrimination and BMI in 74 subjectively olfactory healthy subjects (Besser et al., 2020). This may be linked with brain anatomical changes and research has shown a lower mean olfactory bulb volume among 28 subjects with obesity, compared to 28 control normal-weight subjects (Poessel et al., 2020a). However, there was no relationship between weight status and olfactory function as measured by the TDI olfactory performance test, and a subsequent study from the same group showed no relationship between odor-induced brain responses and BMI (Poessel et al., 2022). Research from the same group found no relationship between BMI and odor sensitivity, but observed a negative relationship between odor sensitivity and insulin sensitivity across normal weight, overweight, and obese subjects (Poessel et al., 2020b).

The mechanisms through which olfactory deficits may lead to overeating are not clear though some suggest that people with diminished odor sensitivity enjoy food less and therefore consume more to derive a similar sensation and food reward.

However, many studies have shown that olfactory loss often leads to a decline in appetite and desire to eat (Arikawa et al., 2020). Current evidence for a systematic relationship between reduced olfactory function, food intake, and diet-related chronic disease remains inconsistent across studies. In addition, it is worth noting that people with anosmia have similar weight trajectories as people with a normal olfactory functioning (Aschenbrenner et al., 2008), and there are no marked differences in food preferences between people with noncongenital anosmia and people with a normal sense of smell (Postma et al., 2020).

12.3 Impact of taste on food choice and intake

12.3.1 *Taste-nutrient relationships in diets across the world*

The sense of taste plays an important role in both food choice and food intake, and has been described as a "gatekeeper" for ingestion, since all foods and beverages must pass over the tongue before being swallowed (Mattes, 2021). Taste functions as a "nutrient-sensor" that provides a signal to the brain and body about the arrival of specific food macronutrients to the brain and metabolic system (De Graaf and Kok, 2010). The role of taste has a biological origin that has evolved since the dawn of mankind, and the functional impact of taste is associated with nutrient and metabolic consequences. From this perspective, it is important to understand how dietary taste patterns differ by weight status and in different diets and food environments across the world. Recent developments in sensory methods have made it possible to objectively quantify the predominant taste qualities of individual foods, and when linked to quantitative dietary intake data, provide novel insights into the taste patterns across a range of healthy and unhealthy dietary diets and geographical regions around the world (Teo et al., 2018).

Table 12.1 shows the average taste intensities of a representative set of foods from countries across the world (Teo et al., 2021; Martin et al., 2014; Lease et al., 2016;

Table 12.1 Average intensities of sweet, sour, bitter, umami, salt, and fat sensation on a 100 mm line scale across representative food supplies across the world. Taste intensities were rated with the help of the spectrum method (Meilgaard, Civille & Carr, 2007), where subjects were provided with anchored points on the line scale with the help of specific concentrations of sucrose for sweet, citric acid for sour, caffeine for bitter, monosodium glutamate for umami, NaCl for salt (Lease et al., 2016; Martin et al., 2014; Teo et al., 2018, 2021; van Langeveld et al., 2017)

	Sweetness	Sourness	Bitterness	Umami	Saltiness	Fat sensation
Australia	27	10	4	8	17	22
Netherlands	22	11	4	8	17	31
Malaysia	20	7	3	15	19	24
France	17	13	8	8	19	21
Singapore	18	6	7	11	14	22

van Langeveld et al., 2017, 2018). Average taste intensities are highest for sweet, salt, and fat sensation, and lowest for bitter. Sour taste mainly comes together with sweet taste in fruit products and drinks (Teo et al., 2021; van Langeveld et al., 2018). Table 12.1 suggests that the average umami intensity may be somewhat higher in the two Asian countries, Malaysia and Singapore, compared to the three countries with a Western diet, i.e., France, Australia, and the Netherlands. Overall, the rated taste intensities are not dissimilar across these geographically diverse food supplies (Table 12.1), suggesting there is a relatively narrow range of acceptable taste intensities across cultures, despite wide dynamic ranges of taste intensities available. For example, for salt intensity it is clear that people will tend not to accept diets that are very low in salty taste, but they also refuse diets that are too high in salt taste intensity. Table 12.2 pools data from a number of published studies on taste patterns in diets around the world, and shows the associations between the taste intensities of sweet, umami, salt, and fat sensation, and energy content, carbohydrate, protein, salt, and fat content. These data combine measures from over 2000 different individual foods rated for their predominant taste properties, and highlight associations between rated taste intensity and the presence of a macronutrient substrate that reflects this taste. The strength of the associations suggests that taste quality and intensity signal the presence of corresponding macronutrient substrates across representative samples of foods from diverse food environments across the world. It is often suggested that sweet taste intensity can act as a proxy indicator of a foods energy content. The data summarized in Table 12.2 show that sweetness intensity is a poor predictor of food energy content and that “fat” sensation and “fat-salty” combinations are more highly correlated with the kcal content of foods.

Comparison of taste intensity data from these studies in Europe, America, and Asia suggests that despite the enormous variety of food products and cuisines around the world, dietary taste patterns tend to have similar patterns and taste-nutrient relationships tend to be similar across different food supplies. In various critiques on modern diets it is often argued that taste-nutrient relationships are corrupted by food processing (Teo et al., 2021). These results demonstrate that the nutrient-signaling function of taste remains intact across a wide range of modern food environments and levels of food processing around the world.

Whereas taste in general has a clear role to play in nutrient selection and intake, it is also clear that this varies considerably with taste quality, since sweet, fatty, salty, and savory are often associated with higher sensory appeal and energy intake, whereas bitter and sour tastes are more often associated with organic acids and bitter glycoside compounds found in vegetables. The following sections profile the role of specific taste qualities in food choice and intake.

12.3.2 Bitterness

We are born with an innate aversion to strong bitter tastes, and the average contribution of bitter taste to energy intakes across diets globally tends to be quite low, either due to bitter foods being infrequently consumed or bitter products often being low in energy. The contribution of bitter tasting food to the total energy intake is below 10% in the

Table 12.2 Correlation coefficients (× 100) between basic taste intensities of sweet, umami, salt, and fat sensation, and sugar, carbohydrate, protein, salt, fat, and kcal content of food supplies across the world. Taste intensities were assessed with the spectrum method as referred to in Table 12.1, and nutrient concentration were derived from food composition tables.

	Number of foods	**Sweet Sugar**	**Sweet Carbohydrates**	**Umami protein**	**Salt Sodium**	**Fat sensation Fat**	**Sweet Kcal**	**Umami Kcal**	**Salt Kcal**	**Fat sensation Kcal**
Australia	377	70	41	27	64	65	−08	09	33	53
USA	237	71	42	n.a.	72	n.a.	11	n.a.	43	n.a.
Netherlands	489	82	54	54	69	75	11	00	22	58
Malaysia	423	62	33	51	52	42	04	04	16	26
France	350	84	57	62	77	72	−11	29	44	64
Singapore	189	73	38	48	62	61	29	−05	22	44

Adapted from Lease, H., Hendrie, G.A., Poelman, A.A.M., Delahunty, C. & Cox, D.N., 2016. A Sensory-Diet database: a tool to characterise the sensory qualities of diets. Food Qual. Prefer. 49, 20−32; Martin, C., Visalli, M., Lange, C., Schlich, P. & Issanchou, S., 2014. Creation of a food taste database using an in-home "taste" profile method. Food Qual. Prefer. 36, 70−80; Teo, P.S., Van Langeveld, A.W., Pol, K., Siebelink, E., De Graaf, C., Martin, C., Issanchou, S., Yan, S.W. & Mars, M., 2018. Training of a Dutch and Malaysian sensory panel to assess intensities of basic tastes and fat sensation of commonly consumed foods. Food Qual. Prefer. 65, 49−59; Teo, P.S., Tso, R., Van Dam, R.M. & Forde, C.G., 2021. Taste of modern diets: the impact of food processing on nutrient sensing and dietary energy intake. J. Nutr. In press; Van Langeveld, A.W., Gibbons, S., Koelliker, Y., Civille, G.V., De Vries, J.H., De Graaf, C. & Mars, M., 2017. The relationship between taste and nutrient content in commercially available foods from the United States. Food Qual. Prefer., 57, 1−7.

diets of the Netherlands, Malaysia, and Singapore (Table 12.1). Across the global diets profiled bitter taste most often comes from drinks like black coffee, tea, and/or alcoholic beverages. These foods often tend to be lower in energy but often have another postingestive reinforcing element that conditions a preference for the bitter taste, and associates bitterness consumption and "reward" (Yeomans et al., 2000). For example, coffee bitterness can be reinforced by the presence of the bitter tasting cardiovascular stimulant caffeine, whereas bitter alcoholic beverages provide postingestive reinforcement through the positive effects associated with alcohol intake (Al Mansouri et al., 2014).

The bimodal trait genetic sensitivity to the taste of bitter compounds has been termed "PROP" status, where numerous studies have tried to link sensitivity to bitterness with resultant dietary patterns and health status. This has led to ambiguous results with several early reports suggesting a link between PROP and BMI (Tepper and Nurse, 1998), while others have linked PROP taster status to vegetables (Drewnowski et al., 2000), alcohol (Duffy et al., 2004), and fat perception and intake (Yackinous and Guinard, 2001, 2002). However, results have been inconsistent and attempts to replicate these findings and predict dietary intake patterns as a function of PROP status have not been successful. Although PROP sensitivity is likely to influence perceptual responses, our food preferences evolve and are learned through repeated exposures, and PROP taster status does not seem to consistently affect food preferences, dietary patterns, or weight status (Stoner et al., 2019; De Toffoli et al., 2019). For example, an initial disdain for bitter vegetables among PROP tasters can be overcome through repeated exposure to produce a higher acceptance (Nor et al., 2021).

Bitter taste receptors (T2R's) are expressed throughout the alimentary canal, starting at the tongue, and running throughout the stomach and gastrointestinal tract (Harmon et al., 2021). Beyond a simplified role in food choice and liking, bitter taste receptors are now thought to play a key role as "chemosensory sentinels" that help to regulate our endocrine, behavioral, and immunological responses to bitter compounds. Several groups have leveraged the discovery of bitter taste receptors in the gut to study the potential impact of intragastric delivery of bitter substances on gastric emptying, satiety, and biological markers related to satiation and satiety (see (Rezaie et al., 2021; Feinle-Bisset and Horowitz, 2021). These results are promising and merit further consideration to better understand how T2R's can influence metabolic responses and understand whether intragastric infusion can reproducibly impact energy intake and metabolism and gastric emptying.

12.3.3 Sourness

Sour taste is primarily associated with the presence of organic acids in foods and beverages and is associated with unripe fruits or foods spoiled by microorganisms (Salles, 2021). Alongside an innate dislike for bitterness is an inborn aversion toward foods with a strong sour taste. However, the contribution of "sourness" to dietary energy intakes is higher than that of bitterness and mainly originates from sweet-sour tasting foods such as fruits/fruit juices, soft drinks, and sweetened yoghurt drinks. There are virtually no foods/drinks that only have a sour taste, and most sourness is consumed as a combination of sweetness and sourness in foods and beverages. The diets in the Netherlands, France, Malaysia, and Singapore each contain a cluster of foods/drinks that are characterized by a combination of a high sweetness/high sourness and low intensity of the other tastes and fat sensation. These sweet-sour tasting foods contribute to the total energy content of the diet with between 10%−15% in the Dutch diet, and 6%−9% in the Malaysian and Singaporean diet (Teo et al., 2018, 2021; van Langeveld et al., 2017).

Children tend to have higher sourness preferences than adults, and are more tolerant of higher sour tastes (Forestell and Mennella, 2015). Liem et al. (2004) observed that there was a substantial group of children who liked foods and drinks with a strong sourness (Liem et al., 2004). Children that had a higher liking for sourness also score higher on sensation seeking, suggesting that sourness has an arousing, energizing effect. An increased preference for sour foods was related to higher fruit consumption (Liem and Russell, 2019).

As with bitterness, the importance of sour taste may not simply be in its role in guiding food preferences, as sour taste induces a much stronger cephalic phase saliva response compared to the other taste primaries (Neyraud et al., 2009). The rationale is that saliva buffers the low pH of sour organic acids, and therefore protects the oral mucosa from damage. Even the thought of a sour taste is sufficient to produce a salivary response (Neyraud et al., 2009). Recent research suggests sour taste may be instrumental in inducing a swallowing responses among patients with dysphagia (Dietsch et al., 2019), suggesting an important application of sour taste intensity for clinical populations in the future.

12.3.4 Saltiness

Salt taste and umami taste are distinct qualities, with independent receptor systems and molecular transduction mechanisms; however, in practice across the food supply salt and umami taste qualities are highly correlated (Teo et al., 2018, 2021; van Langeveld et al., 2017). Correlations between salt and umami intensity across the food supplies were 0.66 ($n = 590$) in France (Martin et al., 2014) and 0.72 ($n = 377$) in Australia (Lease et al., 2016) with similar correlations found in the Netherlands and Malaysia (Teo et al., 2018). These correlations persist, despite the fact that these ratings were obtained using sensory panels that had been trained to distinguish between umami and salt taste qualities. Electrolytes such as NaCl are essential nutrients, playing a critical role in regulating osmotic pressure in cells and maintaining muscle function and nerve cell signaling. Urinary electrolyte levels are a marker of hydration status and secretion provides the body with an opportunity to rebalance electrolyte levels that are too high (Polycarpe et al., 2004). Conversely, sodium-deficient animals develop a craving for salt (Leshem, 2009), and salt perception and intake are related to fluid intake and mineral balance (Leshem, 2020).

Salty tasting foods play an important role in moderating energy intake within the modern food environment, and in the Netherlands "salty/umami/fatty" cluster contributes to approximately 20%−25% of all calories consumed in the diet (van Langeveld et al., 2018). These figures rise even higher in Malaysia and Singapore where salty/

umami/fatty foods comprise approximately 50% of calorie intake (Teo et al., 2021). A high liking and intake for salty-fatty foods is also associated with higher prevalence of obesity (Teo et al., 2021; van Langeveld et al., 2018). One possible reason for this association between salt intensity and higher energy intakes may be due to our reduced ability to discriminate between fat-contents at higher salt taste intensity (Bolhuis et al., 2016, 2018). Research has shown that we can accurately discriminate between fat contents at lower taste intensity (Drewnowski and Schwartz, 1990), but this ability is significantly attenuated when fat is combined with higher taste intensity. Higher salt taste intensity has been shown to promote an increase in energy intake and psycho-hedonic functions of salt-fat mixtures show a 30% increase in energy intake when fat is consumed at an optimal salt intensity (Bolhuis et al., 2016). As such, salt (NaCl) contains no calories but is highly taste active whereas fat is highly energetic (9 kcal/g) but has low taste activity. Evidence to date suggests that the taste-nutrient combination of "salt-fat" contributes disproportionately more to higher energy intakes (Teo et al., 2021; van Langeveld et al., 2018).

Dietary nutrition and health recommendations and reformulation efforts in many countries across the world put on a societal pressure to reduce salt intake. Early studies from the 1980s do suggest that an exposure to a low-salt diet decreases preferences for optimal salt levels in foods (Bertino et al., 1982). Today salt intakes are much higher than recommended and the decline in average salt intake in various countries remains very slow (Hyseni et al., 2017). High salt concentrations can promote palatability to an optimum level, but could salt taste intensity also play a role in the onset of satiation? Previous research has explored the impact of salt intensity on satiation and energy intake within a meal of tomato soups that were equally palatable but different in the salt intensity (Bolhuis et al., 2012). Preferred salt concentration was measured using the psycho-hedonic function for each individual subject, and salt intensity was raised and lowered per participant to ensure perceptible intensity changes in equally palatable versions of the tomato soups. A first study demonstrated that salt intensity had no impact on ad libitum intake when soup was the only food served to a group of hungry participants. However a follow-up study using the same stimuli showed that when high-salt soup was served with an ad libitum sandwich lunch, energy intake was 8% lower in the higher salt condition compared to the low salt condition suggesting that higher intensity increased the onset of satiation during consumption (Bolhuis et al., 2010). These small effects merit consideration, as they suggest the potential application of taste *intensity* to help moderate or reduce intake within a meal, without the need for additional calories of a reduction in meal satisfaction. Further research is needed to clarify the potential of such an approach across different taste qualities and product formats.

12.3.5 Umami

Umami or savory taste has been associated with the detection and intake of dietary protein, whereas salt taste perception seems more related to the maintenance of fluid and mineral balance. As shown in Table 12.2, umami taste intensity in food is moderately correlated with the protein content across food supplies in Malaysia, Singapore, the

Netherlands, Australia, and France. The issue of protein intake is one of the most crucial and important issues in the field of nutrition, health, and sustainability, where recent years have seen an increasing trend to move away from animal protein toward plant-based proteins in the food supply (Tso et al., 2021). A sufficient intake of high-quality proteins is an essential prerequisite of good nutrition across the world (Tso and Forde, 2021).

Umami was first isolated and discovered by Ueda in 1908 (Fuke and Shimizu, 1993) and its characteristic "delicious" taste has been recognized as a basic taste primary for more than 30 years (Beauchamp and Pearson, 1991). The rated umami intensity of the Malaysian and Singaporean diets is higher than that of diets in Australia, France, and the Netherlands (Table 12.1) and is also reflected in the contribution of umami/salty/fatty foods to energy intakes in Singapore and Malaysia. Umami-fatty taste clusters contribute more than 50% to energy intakes in these countries, whereas in the Netherlands this contribution is about 20%–25% (Martin et al., 2014; Teo et al., 2021; van Langeveld et al., 2018). The central role of protein in guiding dietary choice and intake has been promoted through the protein leverage theory of Simpson and Raubenheimer (2005), who argue that protein intake is tightly regulated as a proportion of dietary energy intake in humans and other species. The idea of a constant relative contribution of protein to dietary energy intake is reinforced by various data sources and in the Netherlands protein intake has been constant since the early 1980s, with an average level of around 80 g per person per day (Van Rossum et al., 2020). A recent paper highlights that protein intakes are more stable than carbohydrate and fat intakes, such that pooled data from 15 countries encompassing men and women from different ethnic and socioeconomic, weight status groups, at different stages of their lifespan and varying in physical activity, the protein intake only varied between 15.3% and 18.5% energy (Lieberman et al., 2020). Our protein intakes and turnover are tightly regulated, and given umami taste intensity is associated with a food's protein content, the implication is that taste can act as an environmental protein cue to stimulate intake and offset the risk of dietary imbalances.

Whereas the protein leverage has been widely demonstrated in animals and insects, much fewer studies have been conducted to study human food choice and intake for protein. In a 14-day fully controlled diet intervention, 37 subjects were exposed to diets that were high or low in protein and subsequent food choice and intake were studied (Griffioen-Roose et al., 2012b). After a protein deficit, food preferences and food intake pivot toward more umami tasting foods showing adaptive changes in dietary intakes to compensate for deviations in protein intake and restore adequate protein status. Similarly, it was observed that a 4-day protein-deficit diet led to increases in appetite for something savory and a higher intake of savory tasting foods, suggesting that protein intake is regulated and is operational through temporal changes in umami preferences (Gosby et al., 2011). These trials demonstrate the adoption of behavioral strategies to counteract protein imbalance, which becomes operational through an increased preference for savory-high protein umami tasting foods. Further acute studies have also shown the impact of savory taste on subsequent food choice and intake (Masic and Yeomans, 2017). The taste exposure of participants was controlled for a 24-h period to provide predominantly sweet or savory foods, followed by an ad libitum buffet of mixed tastes (Griffioen-Roose et al., 2012a). Taste exposure influenced food choice at the buffet, such that following the sweet diet preference for savory went up, whereas following the savory diet preference for sweetness increased. Importantly, despite these sensory-specific effects of taste on dietary choice, the predominant taste of previous 24-h diet had no effect on overall macronutrient intakes.

Previous research has compared the satiating potential of different taste qualities, based on anecdotal reports that sweet foods are less satiating on kcal per kcal level than savory foods. Early research studies demonstrate that postmeal feelings of fullness are equivalent from savory (umami) and sweet versions of a test meal (De Graaf et al., 1993), and this was later confirmed in terms of energy consumed to fullness (satiation) (Griffioen-Roose et al., 2009). Further research has shown that we compensate in the same way when energy is added to our diets as either a sweet or a savory food (Tey et al., 2018), suggesting that sensory cues are likely to only be influential during consumption, rather than during the intermeal interval. Savory stimulation is thought to have a biphasic role in appetite control (Masic and Yeomans, 2014), stimulating intake through enhanced preference in some contexts (Hollis and Henry, 2007), but also contributing to earlier satiation or enhanced satiety and reduced energy intake in others (Masic and Yeomans, 2014). For example, umami enhancement trials have successfully demonstrated increased palatability and intake for meals enhanced with monosodium glutamate (MSG) among vulnerable older populations (Mathey et al., 2001; Abbott et al., 2013; Methven et al., 2012), whereas others have failed to replicate this effect (Essed et al., 2007). Research has also successfully demonstrated that when meals are enhanced with umami, it can produce a small but significant change in energy intake or reduce later food intake (Miyaki et al., 2016; Imada et al., 2014), whereas others have shown effects only on rated appetite but not later energy intake (Anderson et al., 2018; Carter et al., 2011). Overall, the effect of savory taste enhancement has provided equivocal results in terms of energy intake, suggesting that if there is likely a small impact on intake and satiety, and that this is highly dependent on food, consumption context, and intensity of the tastant. In addition to its functional role in food intake, the primary savory/umami compound MSG has also been shown to support salt reduction and food reformulation (Katsuyuki, 2020) by ameliorating the reduction in palatability often associated with low salt versions of foods, where added MSG has been shown to facilitate a salt reduction from 0.9% to 0.3% without reducing liking (Hayabuchi et al., 2020).

A related sensation is the *Koku* perception of "mouth fullness" which is not in itself a taste, but an oral sensation that has been observed to contribute to savory intensity, complexity, and duration. This sensation is stimulated by *kokumi* tripeptides that are low-calorie taste and mouthfeel enhancers that enhance sensations of mouthfulness, continuity, and complexity, often mimicking the sensory impact of fat. Whereas much research to date has focused on their sensory perception, preliminary recent findings demonstrate that addition of *kokumi* compounds can enhance sensory dimensions linked to calorie expectations, and promote higher estimated calories and expected fullness across a series of equicaloric broths (Tang et al., 2020). Future research should further aim to explore the potential of *Kokumi* compounds to support calorie reduction while maintaining a products sensory appeal.

12.3.6 Sweetness

In contrast to bitter and sour tastes, humans and other mammals are born with an innate liking for sweetness (Cowart, 1981). Exposure to sweetness is pleasant, calming, and soothing and has an analgesic effect among children, such that sweet stimuli are often used to distract from the pain of vaccination in young babies (see Harrison et al. (2010), for a review). The dictionary definition of "sweet" is something pleasant, satisfying, agreeable, and delightful.

The psychohedonic optimal sweetness is significantly higher in infants than in adults, and slowly declines from early infancy throughout childhood and into early adolescence (Liem and Mennella, 2002; De Graaf and Zandstra, 1999). This figure aligns with the observation that the contribution of mono-and disaccharides to energy intake is about 33% in toddlers and declines to about 20% in adulthood, and these figures have been stable in the Netherlands since the 1980s (Van Rossum et al., 2020). Recent data on the predominant taste of calories consumed in the Dutch diet show that sweet-sour and sweet-fatty tasting foods comprise approximately 25%—30% of the energy intake (van Langeveld et al., 2018). However, much of the societal narrative around sweetness centers on the "sweet tooth," and the excessive energy consumed from sugary soft drinks and foods considered as discretionary calories that promote energy consumption and eventually lead to obesity (Anderson, 1995). The rationale of this reasoning is that sweetness is pleasant and that people with obesity tend to consume a greater proportion of their energy from sweet foods than people in the normal weight range. However, this reasoning is not supported by available data. As is clear from Table 12.2, sweetness intensity is poorly correlated with the energy content of food, and this has been observed across the global diet from the USA, to Europe and Asia. A further proposition is that people with obesity must have a higher liking for sweetness compared to those in the normal weight range, but again this hypothesis is not backed by data. Multiple studies since the early 1980s fail to demonstrate a clear relationship between weight status and the psychohedonic function for sweetness (Cox et al., 2016). Experimental and observational data have failed to show a difference in sweetness preference by weight status in children (Bobowski and Mennella, 2017) or adults (Cox et al., 1998). Consumption of sweet foods also does not stratify by weight status (Teo et al., 2021; van Langeveld et al., 2018).

In the modern food environment there is pressure to reduce sugar from foods and beverage to reduce their energy content. However, what remains less clear is whether sugar content or the associated sweetness perception is the driver of consumption. Few trials to date have explored whether exposure is driving preferences and intake for sweet foods, and today it remains unclear whether high exposure to sweetness leads to increased liking for high "sweetness" level or conversely a low sweetness exposure leads to lower preference for "sweetness." A recent systematic review showed no consistent data in this direction, and observed that whereas short-term effects of sweetness exposure lead to a decline in sweetness liking, there are limited available data to conclude on the longer-term implications of sweetness exposure (Appleton et al., 2018). One RCT to date has controlled for dietary exposure to sweetness and only found transitory changes in rated sweetness intensity, though no sustained changes in sweet liking (Wise et al., 2015). Further research is needed to better understand whether sweetness preferences are hard-conditioned from early life, or are malleable in response to tastant exposure within our food environment.

Earlier in the chapter we highlighted that umami preferences adapt in response to deviations in protein status, and sweetness perception also plays an important role in our metabolic response to sugar (mono- and disaccharide) consumption. Consumption of simple carbohydrates stimulates early cephalic release of enzymes and hormones, such that over time, sweetness becomes predictive of sugar and carbohydrate ingestion, and stimulates insulin release (Härtel et al., 1993; Teff et al., 1995). However, others have failed to show a clear and reproducible relationship between sweet stimulation and subsequent cephalic phase responses; therefore, the role of sweetness stimulation on carbohydrate-insulin metabolism remains an important debate among researchers in the sensory nutrition field. Relationships between sweet taste and the subsequent delivery of energy are learned, so any disruption in the link between the sensory cue (sweet taste) and subsequent nutrient deliver (carbohydrates/energy) content could potentially disrupt these learned associations and impact later food intake behavior. It has been suggested by some researchers that decoupling of sweetness from energy delivery may enhance appetite stimulating excessive energy intakes, or disruption of the normal glycemic response to carbohydrate ingestion (Swithers and Davidson, 2008; Swithers et al., 2010; Pepino, 2015). However early findings in animal studies have not been replicated in humans, and several recent meta-analyses of studies have shown use of nonnutritive sweeteners in place of sugar support reductions in energy intake, body weight, and BMI (Toews et al., 2019; Rogers et al., 2016). The balance of evidence supports the role of low and no-calorie sweeteners in reducing sugar content while still maintaining the sensory appeal.

12.3.7 Fat sensation

Recent studies have shown that free fatty acids (FFAs) can elicit a “taste” response (Keast and Costanzo, 2015), and this taste of fatty acids is believed to influence fatty metabolism during digestion (Mattes, 2009). This sensation has been described as a distinct sensory quality and christened “oleogustus,” to delineate the taste of free fatty acids on the tongue (Running et al., 2015), from other mouthfeel sensations associated with fat consumption. Whereas results have reproducibly shown free fatty acids such as linoleic or oleic acid to elicit a taste response, it is also acknowledged that this taste quality is difficult to describe and recognize, and people tend to articulate this sensation quite differently. The qualitative description of FFAs and separation of the taste of fatty acids from the attendant mouthfeel properties of triglycerides have made it challenging to characterize the impact of these compounds in everyday food choice and intake, where fat is typically consumed in the form of oils, and free fatty acids are typically a marker of rancidity or spoilage (Mattes, 2021). Nevertheless, sensitivity to the oral sensations arising from FFA consumption are likely to vary within the population and previous research has suggested that people with a lower sensitivity to FFAs are at an increased obesity risk (Stewart et al., 2010, 2011). Further research has shown that participants in the overweight to obese weight range had a lower sensitivity for the taste of free fatty acids compared to normal weight subjects (Liu et al., 2016). People have been shown to adapt to high and/or low-fat levels in food, and this has an impact on their subsequent ad libitum energy intake and body weight, suggesting that fatty acid taste sensitivity is influenced by the taste environment rather than purely by genetics (Costanzo et al., 2018). Further research is needed to establish a clear role for fatty acid taste in food perception and preference and the development of dietary patterns.

Fat makes a significant contribution to daily energy intakes, and is by far the most energy dense macronutrient (9 kcal/g), compared to protein and carbohydrates (4 kcal/g). Fat is omnipresent in diets across the world and the sensory appeal of fat/sugar and fat/salt mixtures in driving food preference has been widely studied (Drewnowski, 1997). In several recent comparisons of the relative contribution of different taste clusters to daily energy intakes, it was observed that in Malaysia and Singapore "savory-fatty" tasting foods contribute more than 50% to total energy intakes, compared to 20%−25% in the Netherlands (Teo et al., 2018, 2021; van Langeveld et al., 2018). Conversely, for "sweet-fatty" foods the contribution is higher in the Netherlands (20%−25%) than in Asia (5%−10%). There are several possible reasons why fat sensation is universally regarded as pleasant. Fat liking may be conditioned through flavor-nutrient conditioning where we learn to associate the sensory sensation of fat with the positive postingestive experience of fullness and satisfaction, which can reinforce the initial hedonic appeal (Kern et al., 1993). The addition of fat to food also makes it easier to eat, providing a built-in source of lubrication that makes food softer, easier to chew, and contributes to oral comfort and an increased eating rate (Bolhuis and Forde, 2020). Adding a fat-rich topping to bread or crackers enhances bolus formation through improved lubrication and ensures a food that requires less chewing and can be eaten at a faster rate (Van Eck et al., 2019). Fat also acts as a reservoir for many nonpolar flavor compounds, and a food's fat content strongly influences the temporal release of volatile aroma compounds during consumption (Brauss et al., 1999; Relkin et al., 2004; Paravisini and Guichard, 2016). By extension, one of the challenges associated with fat reduction is that low-fat foods often shift the temporal release profile of aroma compounds due to differences in partitioning and temporal release of lipophilic aroma compounds relative to hydrophilic compounds (Plug and Haring, 1993). As such, fat, unlike the other primary taste qualities, has a multimodal effect on perception and exerts a strong dynamic influence on flavor release and oral processing, and a disproportionately large contribution to energy intakes.

Fat contributes to mouthfeel and texture perception, but in reciprocal manner, texture and the related oral processing behaviors contribute to flavor release and perception. In addition to its role in flavor perception, food texture informs our oral processing behaviors and plays a central role in moderating the flow of calories through our diets. This is discussed in the following section.

12.4 Impact of texture on eating rate and food intake

12.4.1 Texture oral processing and the food intake

Food texture is often an overlooked food sensory property, and in some cases only merits consideration when it deviates from expectations (Szczesniak, 2002). However, texture is central to our appraisal of food quality (Kilcast and Lewis, 1990), freshness, and acceptance and as described earlier, can significantly influence the rate and extent of food taste and odor substances from the food matrix during consumption (Gierczynski et al., 2011). For example, harder foods of plant origin need to be masticated and broken down before their taste and smell compounds can be released from within the cell walls to be perceived (Bonneau et al., 2018). Mastication is necessary for dynamic temporal changes in flavor release and perception, but also to prepare solid foods for safe swallow, where the initial structure is deformed to a fragmented bolus, lubricated agglomerated safety swallowed (Witt and Stokes, 2015). A foods trajectory from initial structure to bolus swallow has been described by the "mouth-process model," which describes the specific changes in structure, size, and lubrication needed for a bolus to reach the swallow phase (Hutchings and Lillford, 1988). This model was originally developed to describe the changes required in bolus form and texture to achieve safe swallow, but when we overlay additional information on oral processing behaviors (i.e., bite size, chews per bite, orosensory exposure time) and eating speed (fast/slow), it is also a useful model within which to conceive the impact of food texture on habitual eating behaviors (Fig. 12.1). This figure illustrates the

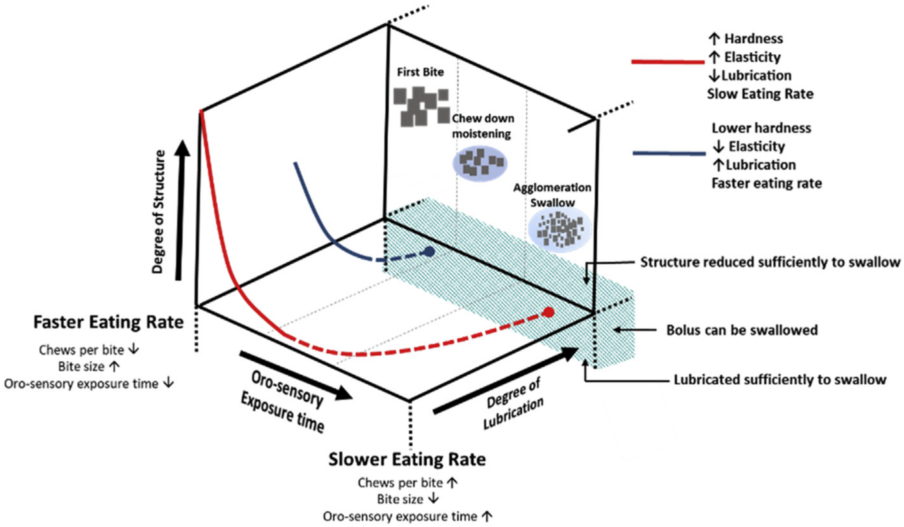

Figure 12.1 Mouth process model of food oral breakdown which illustrates the impact of food texture and lubrication on oral processing behaviors and eating speed.
Image adapted by M. Stieger from Hutchings, J.B. & Lillford, P.J., 1988. The perception of food texture - the philosophy of the breakdown path. J. Text. Stud. 19, 103–115.

importance of foods' mechanical properties and lubrication state in moderating the time required to prepare a bolus for swallow (orosensory exposure time) and the rate at which we consume calories during a meal.

Extensive research has highlighted the important role of "food form" on energy intake to satiation and postmeal satiety and shown that we tend to consume more from liquid foods and these foods tend to deliver less fullness post-meal (satiety) on a kcal for kcal basis (Dhillon et al., 2016). Further studies in recent years have illustrated that within food form (liquid, semisolid solid) texture differences can influence both eating rate and energy intake (for a review see Bolhuis and Forde (2020)). Initial findings from semisolid and semiliquid foods highlight the importance of viscosity on eating rate and intake (Zijlstra et al., 2008), and dietary learning (Mars et al., 2009).

Studies reveal that people tend to consume approximately 30% more energy from liquids than semisolids, and these differences in intake were attenuated (12%) but maintained even after controlling for subject eating effort (Zijlstra et al., 2008). Further research with solid foods revealed that we tend to adapt our eating rate in response to the food texture consumed within a meal and increasing the texture challenge can both slow and decrease intake within a meal. Across a trio of controlled feeding studies, harder food texture reduced eating rate and was associated with a 10%−15% reduction in ad-libitum energy intake (Bolhuis et al., 2014; Forde et al., 2013a,c; McCrickerd et al., 2017b). Importantly, these reductions in energy intake did not produce lower sensory appeal (Forde et al., 2013c) or a weaker post-meal satiety response (McCrickerd et al., 2017b) or later compensatory eating (Bolhuis et al., 2014). The implication is that food texture could be used to guide the rate of calorie intake and mitigate potential risks associated with consuming high energy foods at a faster rate (Bolhuis and Forde, 2020). Faster eating rate is now recognized as a risk factor for obesity and diet-related chronic diseases such as type-2 diabetes (Teo and Forde, 2020). The rate at which an individual consumes a meal has been shown to be very consistent over time (McCrickerd and Forde, 2017) and it can be influenced by underlying differences between individuals in their drive to eat (Fogel et al., 2020) and by the texture and properties of the food environment they choose to consume (Bolhuis and Forde, 2020). As such, eating rate is a consistent property of both the individual and the food—a faster eater will eat bread faster than a slow eater, but will also consistently eat yoghurt faster than a slower eater, and in both cases the average eating rate of bread will be slower than that of yoghurt (see van den Boer et al., 2017a) for a comprehensive list of Dutch food eating rates). As eating rate is such an important variable for intake, we first summarize available evidence on why there are differences in eating rate between individuals, and then describe the impact of different food textures on eating rate and intake.

12.4.2 *The origins of differences in eating rate and association with energy intake and obesity*

Large-scale epidemiological studies show that people who self-report to eat faster have a higher risk for obesity than those reporting to eat slower. A systematic review and metaanalysis of 23 studies mainly from Asia showed that eating quickly is positively associated with excess body weight (Ohkuma et al., 2015). These observations have been confirmed both in Western populations (van den Boer et al., 2017b) as well as in Korean (Kang et al., 2021), Japanese (Zhu et al., 2015), and Singaporean populations (Teo et al., 2020a,b). This literature is reviewed in more detail in Teo and Forde (2020).

Habitual eating behaviors, including eating rate, emerge early and remain stable throughout childhood. Research has shown that both genetic and early life food environment can influence the development of eating behavior (Llewellyn et al., 2014), with data from the GEMINI twin cohort showing that among 9−10-year-old British children faster eating rate is a heritable trait that associates with higher BMI (Llewellyn et al., 2008). Subsequent studies have shown that among 4-year-old children faster eating rate is a biobehavioral marker for the development of childhood obesity (Berkowitz et al., 2010). Across a series of studies within the Growing up in Singapore to healthier outcomes (GUSTO) birth cohort, it was observed that 4.5-year-old children who ate faster during an ad libitum test meal consumed significantly more, and tended to have both higher BMI_Z scores and adiposity than children eating at a slower rate (Fogel et al., 2017a,b). This eating behavior was described as “obesogenic” as normal weight children eating faster at 4.5 years continued to do so at a later time point (6 years), and this was associated with increases in BMI_Z score and adiposity at the later timepoints (Forde et al., 2019; McCrickerd et al., 2017a; Quah et al., 2019). Importantly, the transition from early life risk to overweight or obesity in later childhood was only observed among children exhibiting eating behaviors such as faster eating among children in the GUSTO cohort, suggesting eating rate may be an important early life modifiable risk factor for childhood obesity (Fogel et al., 2020).

Few studies exist on adolescent eating rates, but studies in young adults reveal that eating rate is consistent at the individual level, and a strong predictor of ad libitum energy consumption (Martin et al., 2005). Across four separate study groups, when participants were invited to consume the same meal for lunch once a week over four consecutive weeks, individual eating rates on the first week were a strong significant predictor of both later eating rate and energy intake during the subsequent ad libitum meals (McCrickerd and Forde, 2017). This level of consistency suggests that although eating rate can be moderated by the texture properties of the meal consumed, it is also likely strongly influenced by an underlying drive to eat and habitual preferred rate of eating. This has led to speculation that differences in individual eating rates may be driven by an underlying difference in energy requirements which strongly associates with basal metabolic rates and lean muscle mass (Henry et al., 2018; Blundell et al., 2020; Wells et al., 2021). In a preschool population of children, faster eating rates have also been found to associate with higher trait impulsivity, child appetitive traits (Fogel et al., 2018a,b, 2019b), and parental feeding practices (Fogel et al., 2019a), suggesting a wide range of inherited and environmental factors are likely to combine to influence rates of eating. Identifying the eating behaviors that consistently predict greater energy intakes is important to connect genetic predisposition to obesity risk to the biobehavioral eating behaviors that later result in obesity and metabolic dysfunction. This creates new opportunities to intervene and targets specific eating behaviors in early childhood diets (Forde, 2018a; Forde et al., 2019; Fogel et al., 2020). Limited studies to date have targeted eating rate in behavioral interventions to tackle obesity, though evidence suggests this could be an effective approach to changing behavior and body weight. In one trial with children at risk of overweight and obesity, participants were supported to reduce their eating speed through the use of computer-based verbal prompts within a meal which led to reduced eating speed and a clinically significant reduction in BMI. Although further studies are needed to test the long-term impact of these behavioral interventions, initial findings suggest this may be a viable approach (Ford et al., 2010). Whereas digital devices offer control in an experimental setting, the sustained effect and long-term adherence to such regimes remains unknown (Jasper et al., 2016; Zhang and Amft, 2017, 2020). In this regard, a potentially more ecologically meaningful approach would be to manipulate oral processing behavior and eating speed through the application of meal textures. In the next section we describe how food texture been shown to effectively moderate eating speed and intake.

12.4.3 Food texture, eating rate, and energy intake

There is wide natural variation in eating rate (g/min) of foods and meals, and this has been observed across studies that sampled food in different parts of the world. The eating rates of commonly consumed solid foods tend to vary from 10 g/min for foods like puffed rice crackers, tortilla chips, or baked tofu puffs to up to 120 g/min for softer foods like tinned tomato or rice porridge (Congee) (Forde et al., 2017; Forde et al., 2013b; van den Boer et al., 2017a; Viskaal-van Dongen et al., 2011; Ferriday et al., 2016). For liquids and semisolids eating rate is much higher, and can rise to 500−600 g/min for beverages like apple juices, soft drinks, or chocolate milk (van den Boer et al., 2017a; Viskaal-van Dongen et al., 2011). Foods that are eaten slower tend to be consumed with smaller bites, more chews per bite, and a longer orosensory exposure (seconds) than foods that are consumed quickly (Ferriday et al., 2016; Forde et al., 2013a; McCrickerd et al., 2017b).

A systematic review and metaanalysis of studies that have measured eating rate and intake confirmed that energy intake is higher when we eat faster, and this effect persists whether the eating rate is manipulated by instructions (i.e., chew slowly), is prompted by a device (i.e., digital feedback to slow down during a meal), or by changes in food texture (Robinson et al., 2014). Instructing participants to chew more during a meal has been shown to reduce eating rate and meal size, though this approach does not always yield consistent findings (Zhu and Hollis, 2014a,b; Martin et al., 2007; Andrade et al., 2008). A recent systematic review and metaanalysis investigated the effects of sensory and physical characteristics of food on intake and found that textural parameters have a strong consistent effect on satiation such that foods that were harder, chunkier, or more viscous, voluminous led to earlier satiation (Appleton et al., 2021). However despite the consistency of texture-based reductions in eating rate and energy intake, research to date has produced equivocal findings on the impact of texture and meal eating rate on postmeal satiety (Hollis, 2018). Extending the number of chews from 15 to 40 led to an increase in postmeal satiety and associated neuroendocrine satiety hormones following the consumption of a fixed meal (Zhu et al., 2013), whereas participants that naturally ate a fixed portion friend rice meal also reported higher subjective feelings of postmeal satiety (Goh et al., 2020). However, others have failed to show differences in postmeal satiety as a result of eating rate (Choy et al., 2021; Tan et al., 2016) suggesting that the food textures are more influential on the energy intake consumed within a meal to fullness (satiation), and less likely to enhance post-meal fullness in a consistent way that reduces subsequent food intake (satiety).

Beyond the impact of food texture on energy intake, texture-based changes to oral processing have also been shown to influence bolus formation and oral phase of digestion and metabolic responses to food (Forde and Stieger, 2022). A longer chewing time is associated with greater bolus surface area, saliva uptake, a longer time for enzymatic action in the oral cavity, and has been shown to stimulate early glucose release and stimulate a stronger postprandial insulin response (Goh et al., 2020, 2021). Whereas this area has potential to apply texture and behavioral support to a healthy postprandial glucose responses, current findings suggest foods texture is likely to influence temporal changes rather than total glucose (Choy et al., 2021) and differences in eating rate account for individual variability in glycemic responses, rather than having a significant metabolic impact on postprandial glucose responses. Further research is needed to evaluate the potential of texture-based differences in food taken orally to support euglycemia in the future.

12.5 Future directions: application of sensory approaches to public health

The current chapter summarizes available evidence on the impact of smell, taste, and texture on food choice, intake, and nutritional behavior. Whereas nutrition primarily focuses on food composition, and food science on structure and food formulation, the link to consumer choice and intake behavior is sometimes overlooked. The evidence presented in the current chapter highlights that sensory science can be viewed as a “bridge” that connects food and health through an understanding of consumer choice and eating behavior (Forde, 2018a). Optimizing diets through an understanding of how sensory cues influence food choice and eating behaviors represents a largely untapped opportunity for public health nutrition, where sensory approaches can be applied to support future initiatives to design nutritious foods and promote healthy dietary patterns.

Many of the studies presented in the current overview are based on acute, 24-h laboratory-based trials, and further research is now needed to evaluate whether these sensory effects are observed over the longer term and in the real food environment. The growing availability of new noninvasive techniques to track intake behaviors and metabolic responses away from the laboratory (Lasschuijt et al., 2021) make it possible to better understand whether acute variability in eating behaviors observed in a laboratory will have a meaningful long-term impact on metabolic markers of health and disease in consumers’ everyday lives. A challenge for future sensory and nutrition researchers is to transform the acquired insights on the impact of texture on eating rate (g/min) and energy intake rate (kcal/min) into actionable food design principles to promote healthier diets that maintain their sensory appeal.

Across the global food industry significant efforts are underway to reformulate foods to reduce the salt, sugar, fat, and energy content in many categories. Beyond palatability, the studies summarized in the current chapter highlight an important functional role of sensory properties in guiding eating behaviors and moderating food intake. A recent randomized controlled trial (RCT) highlights this further, where consuming a diet comprising highly processed foods has been shown to promote sustained higher energy intakes and weight gain (Hall et al., 2019). Importantly, findings from this RCT also demonstrate that higher energy intake was mediated by the softer texture and higher energy density of foods in the processed diet, highlighting the interplay between sensory (texture) and nutrient properties (energy density) in promoting observed higher energy intakes (Forde et al., 2020). Whereas higher energy intake rates (kcal/min) have been implicated in excess energy intakes within the modern food environment, research presented in Section 12.4.2 of the current chapter offers potential solutions, through the application of food texture to slow and reduce the rate and extent of ad libitum energy intakes. Further, long-term controlled nutrition intervention studies should consider the effects of food sensory properties in addition to composition when developing diet and behavioral approaches to reduce the risk of excess energy intakes.

The recent development of approaches to quantify the sensory intensity of foods and through this link perception to dietary intake patterns was described in Section 12.3.1 (and Tables 12.1−12.2). We have described this approach as “sensory epidemiology,” and it is a powerful approach to explore dietary patterns through the perceptual properties of the foods habitually chosen and consumed. When sensory epidemiology is applied to longer-term cohorts, it will become possible to understand the development of dietary taste and texture patterns that associate with poor cardiometabolic health and all-cause mortality. Future research is needed to understand the long-term impact of dietary interventions, and clarify whether diets lower in sugar or salt result in a shift in sweet and salt taste preferences, and whether these diets can be modified through dietary taste exposure. Salt reformulation has progressed slowly, and overall salt intakes are higher than recommended. Central efforts to reformulate the salt content of foods and diets will be a better understanding of how malleable salt-preferences are, and whether reduced exposure can sustain preferences for reduced salt foods. Recent years have seen the emergence of many low-calorie ingredients that can impart high sweet and savory taste intensity, and future research is needed to understand how these stimuli can be applied to reduce the burden of public health-sensitive nutrients (i.e., salt, sugar, fat) while still maintaining a products sensory appeal and eating pleasure.

Diet-related chronic diseases such as obesity and type-2 diabetes are largely avoidable and are the result of the foods we choose and the quantity and frequency with which we consume them. Acute food choice and energy intake decisions are more strongly influenced by the sensory and cognitive aspects of eating, than the underlying nutritive properties of the food consumed, yet chronic disease and ill-health are influenced by the prolonged exposure to a diet with poor nutritive properties and high energy. The research summarized in the current chapter highlights that a food's sensory properties guide the foods we choose, and the quantity and frequency with which we consume them. A deeper understanding of the relationship between sensory perception, choice, and intake behavior will therefore be central to efforts to moderate habitual dietary patterns and sustain a move to healthier eating patterns.

References

Abbott, R.A., Whear, R., Thompson-Coon, J., Ukoumunne, O.C., Rogers, M., Bethel, A., Hemsley, A., Stein, K., 2013. Effectiveness of mealtime interventions on nutritional outcomes for the elderly living in residential care: a systematic review and meta-analysis. Age. Res. Rev. 12, 967−981.

Al Mansouri, S., Ojha, S., Al Maamari, E., Al Ameri, M., Nurulain, S.M., Bahi, A., 2014. The cannabinoid receptor 2 agonist, β-caryophyllene, reduced voluntary alcohol intake and attenuated ethanol-induced place preference and sensitivity in mice. Pharmacol. Biochem. Behav. 124, 260−268.

Al-Swidi, A., Huque, S.M.R., Hafeez, M.H., Shariff, M.N.M., 2014. The role of subjective norms in theory of planned behavior in the context of organic food consumption. Br. Food J. 116, 0007-070X.

Anderson, G.H., Fabek, H., Akilen, R., Chatterjee, D., Kubant, R., 2018. Acute effects of monosodium glutamate addition to whey protein on appetite, food intake, blood glucose, insulin and gut hormones in healthy young men. Appetite 120, 92−99.

Anderson, G.H., 1995. Sugars, sweetness, and food intake. Am. J.ournal Clin. Nutrit. 62, 195S−201S.

Andrade, A.M., Greene, G.W., Melanson, K.J., 2008. Eating slowly led to decreases in energy intake within meals in healthy women. J. Am. Diet. Assoc. 108, 1186−1191.

Appleton, K., Tuorila, H., Bertenshaw, E., De Graaf, C., Mela, D., 2018. Sweet taste exposure and the subsequent acceptance and preference for sweet taste in the diet: systematic review of the published literature. Am. J. Clin. Nutr. 107, 405−419.

Appleton, K.M., Newbury, A., Almiron-Roig, E., Yeomans, M.R., Brunstrom, J.M., De Graaf, K., Geurts, L., Kildegaard, H., Vinoy, S., 2021. Sensory and physical characteristics of foods that impact food intake without affecting acceptability: systematic review and meta-analyses. Obes. Rev. 1−22, 2021 e13234.

Arikawa, E., Kaneko, N., Nohara, K., Yamaguchi, T., Mitsuyama, M., Sakai, T., 2020. Influence of olfactory function on appetite and nutritional status in the elderly requiring nursing care. J. Nutr. Health Aging 1−6.

Aschenbrenner, K., Hummel, C., Teszmer, K., Krone, F., Ishimaru, T., Seo, H.S., Hummel, T., 2008. The influence of olfactory loss on dietary behaviors. Laryngoscope 118, 135−144.

Beauchamp, G.K., Pearson, P., 1991. Human development and umami taste. Physiol. Behav. 49, 1009−1012.

Berkowitz, R.I., Moore, R.H., Faith, M.S., Stallings, V.A., Kral, T.V., Stunkard, A.J., 2010. Identification of an obese eating style in 4-year-old children born at high and low risk for obesity. Obesity 18, 505−512.

Bertino, M., Beauchamp, G.K., Engelman, K., 1982. Long-term reduction in dietary sodium alters the taste of salt. Am. J. Clin. Nutr. 36, 1134−1144.

Besser, G., Erlacher, B., Aydinkoc-Tuzcu, K., Liu, D.T., Pablik, E., Niebauer, V., Koenighofer, M., Renner, B., Mueller, C.A., 2020. Body-mass-index associated differences in ortho-and retronasal olfactory function and the individual significance of olfaction in health and disease. J. Clin. Med. 9, 366.

Blundell, J., De Graaf, C., Hulshof, T., Jebb, S., Livingstone, B., Lluch, A., Mela, D., Salah, S., Schuring, E., Van Der Knaap, H., 2010. Appetite control: methodological aspects of the evaluation of foods. Obes. Rev. 11, 251−270.

Blundell, J.E., Gibbons, C., Beaulieu, K., Casanova, N., Duarte, C., Finlayson, G., Stubbs, R.J., Hopkins, M., 2020. The drive to eat in homo sapiens: energy expenditure drives energy intake. Physiol. Behav. 219, 112846.

Bobowski, N., Mennella, J.A., 2017. Personal variation in preference for sweetness: effects of age and obesity. Child. Obes. 13, 369.

Boesveldt, S., De Graaf, K., 2017. The differential role of smell and taste for eating behavior. Perception 46, 307−319.

Bolhuis, D.P., Forde, C.G., 2020. Application of food texture to moderate oral processing behaviors and energy intake. Trends Food Sci. Technol. 106, 445−456.

Bolhuis, D.P., Lakemond, C.M., De Wijk, R.A., Luning, P.A., De Graaf, C., 2010. Effect of salt intensity on ad libitum intake of tomato soup similar in palatability and on salt preference after consumption. Chem. Sens. 35, 789−799.

Bolhuis, D.P., Lakemond, C.M., De Wijk, R.A., Luning, P.A., De Graaf, C., 2012. Effect of salt intensity in soup on ad libitum intake and on subsequent food choice. Appetite 58, 48−55.

Bolhuis, D.P., Forde, C.G., Cheng, Y., Xu, H., Martin, N., De Graaf, C., 2014. Slow food: sustained impact of harder foods on the reduction in energy intake over the course of the day. PLoS One 9, e93370.

Bolhuis, D.P., Costanzo, A., Newman, L.P., Keast, R.S., 2016. Salt promotes passive overconsumption of dietary fat in humans. J. Nutrit. 146, 838−845.

Bolhuis, D.P., Costanzo, A., Keast, R.S., 2018. Preference and perception of fat in salty and sweet foods. Food Qual. Prefer. 64, 131−137.

Bonneau, A., Boulanger, R., Lebrun, M., Maraval, I., Valette, J., Guichard, É., Gunata, Z., 2018. Impact of fruit texture on the release and perception of aroma compounds during in vivo consumption using fresh and processed mango fruits. Food Chem. 239, 806−815.

Brauss, M.S., Linforth, R.S., Cayeux, I., Harvey, B., Taylor, A.J., 1999. Altering the fat content affects flavor release in a model yogurt system. J. Agric. Food Chem. 47, 2055−2059.

Brunstrom, J.M., 2007. Associative learning and the control of human dietary behavior. Appetite 49, 268−271.

Carter, B.E., Monsivais, P., Perrigue, M.M., Drewnowski, A., 2011. Supplementing chicken broth with monosodium glutamate reduces hunger and desire to snack but does not affect energy intake in women. Br. J. Nutr. 106, 1441−1448.

Choy, J., Goh, A., Chatonidi, G., Ponnalagu, S., Wee, S., Stieger, M., Forde, C., 2021. Impact of food texture modifications on oral processing behaviour, bolus properties and postprandial glucose responses. Curr. Res. Food Sci. 4, 891−899.

Costanzo, A., Nowson, C., Orellana, L., Bolhuis, D., Duesing, K., Keast, R., 2018. Effect of dietary fat intake and genetics on fat taste sensitivity: a co-twin randomized controlled trial. Am. J. Clin. Nutrit. 107, 683−694.

Cowart, B.J., 1981. Development of taste perception in humans: sensitivity and preference throughout the life span. Psychol. Bullet. 90, 43−73.

Cox, D.N., Galen, M., Hedderley, D., Perry, L., Moore, P.B., Mela, D.J., 1998. Sensory and hedonic judgments of common foods by lean consumers and consumers with obesity. Obesity 6, 438−447.

Cox, D.N., Hendrie, G.A., Carty, D., 2016. Sensitivity, hedonics and preferences for basic tastes and fat amongst adults and children of differing weight status: a comprehensive review. Food Qual. Prefer. 48, 359−367. Part B.

De Araujo, I.E., Rolls, E.T., Velazco, M.I., Margot, C., Cayeux, I., 2005. Cognitive modulation of olfactory processing. Neuron 46, 671−679.

De Graaf, C., Kok, F.J., 2010. Slow food, fast food and the control of food intake. Nat. Rev. Endocrinol. 6, 290−293.

De Graaf, C., Zandstra, E.H., 1999. Sweetness intensity and pleasantness in children, adolescents, and adults. Physiol. Behav. 67, 513−520.

De Graaf, C., Schreurs, A., Blauw, Y.H., 1993. Short-term effects of different amounts of sweet and nonsweet carbohydrates on satiety and energy intake. Physiol. Behav. 54, 833−843.

De Graaf, C., De Jong, L.S., Lambers, A.C., 1999. Palatability affects satiation but not satiety. Physiol. Behav. 66, 681−688.

De Graaf, C., Kramer, F.M., Meiselman, H.L., Lesher, L.L., Baker-Fulco, C., Hirsch, E.S., Warber, J., 2005. Food acceptability in field studies with US army men and women: relationship with food intake and food choice after repeated exposures. Appetite 44, 23−31.

De Toffoli, A., Spinelli, S., Monteleone, E., Arena, E., Di Monaco, R., Endrizzi, I., Gallina Toschi, T., Laureati, M., Napolitano, F., Torri, L., 2019. Influences of psychological traits and PROP taster status on familiarity with and choice of phenol-rich foods and beverages. Nutrients 11, 1329−1336.

De Vries, R., De Vet, E., De Graaf, K., Boesveldt, S., 2020. Foraging minds in modern environments: high-calorie and savory-taste biases in human food spatial memory. Appetite 152, 104718.

Dhillon, J., Running, C.A., Tucker, R.M., Mattes, R.D., 2016. Effects of food form on appetite and energy balance. Food Qual. Prefer. 48, 368−375. Part B.

Dietsch, A.M., Dorris, H.D., Pearson Jr., W.G., Dietrich-Burns, K.E., Solomon, N.P., 2019. Taste manipulation and swallowing mechanics in trauma-related sensory-based dysphagia. J. Speech, Lang. Hear. Res 62, 2703−2712.

Drewnowski, A., Schwartz, M., 1990. Invisible fats: sensory assessment of sugar/fat mixtures. Appetite 14, 203−217.

Drewnowski, A., Henderson, S.A., Hann, C.S., Berg, W.A., Ruffin, M.T., 2000. Genetic taste markers and preferences for vegetables and fruit of female breast care patients. J. Am. Diet Assoc. 100, 191−197.

Drewnowski, A., 1997. Why do we like fat? J. Am. Diet. Assoc. 97, S58−S62.

Duffy, V.B., Davidson, A.C., Kidd, J.R., Kidd, K.K., Speed, W.C., Pakstis, A.J., Reed, D.R., Snyder, D.J., Bartoshuk, L.M., 2004. Bitter receptor gene (TAS2R38), 6-n-propylthiouracil (PROP) bitterness and alcohol intake. Alcohol. Clin. Exp. Res. 28, 1629−1637.

Essed, N.H., Van Staveren, W.A., Kok, F.J., De Graaf, C., 2007. No effect of 16 weeks flavor enhancement on dietary intake and nutritional status of nursing home elderly. Appetite 48, 29−36.

Fedoroff, I.D.C., Polivy, J., Herman, C.P., 1997. The effect of pre-exposure to food cues on the eating behavior of restrained and unrestrained eaters. Appetite 28, 33−47.

Fedoroff, I.D.C., Polivy, J., Herman, C.P., 2003. The specificity of restrained versus unrestrained eaters' responses to food cues: general desire to eat, or craving for the cued food? Appetite 41, 7−13.

Feinle-Bisset, C., Horowitz, M., 2021. Appetite and satiety control—contribution of gut mechanisms. Nutrients 13 [Online].

Ferriday, D., Brunstrom, J.M., 2008. How does food-cue exposure lead to larger meal sizes? Br. J. Nutr. 100, 1325−1332.

Ferriday, D., Bosworth, M.L., Godinot, N., Martin, N., Forde, C.G., Van Den Heuvel, E., Appleton, S.L., Mercer Moss, F.J., Rogers, P.J., Brunstrom, J.M., 2016. Variation in the oral processing of everyday meals is associated with fullness and meal size; A potential nudge to reduce energy intake? Nutrients 8, 315.

Fogel, A., Goh, A.T., Fries, L.R., Sadananthan, S.A., Velan, S.S., Michael, N., Tint, M.-T., Fortier, M.V., Chan, M.J., Toh, J.Y., 2017a. Faster eating rates are associated with higher energy intakes during an ad libitum meal, higher BMI and greater adiposity among 4· 5-year-old children: results from the growing up in Singapore towards healthy outcomes (GUSTO) cohort. Br. J. Nutr. 117, 1042−1051.

Fogel, A., Goh, A.T., Fries, L.R., Sadananthan, S.A., Velan, S.S., Michael, N., Tint, M.T., Fortier, M.V., Chan, M.J., Toh, J.Y., 2017b. A description of an 'obesogenic'eating style that promotes higher energy intake and is associated with greater adiposity in 4.5 year-old children: results from the GUSTO cohort. Physiol. Behav. 176, 107−116.

Fogel, A., Fries, L.R., Mccrickerd, K., Goh, A.T., Quah, P.L., Chan, M.J., Toh, J.Y., Chong, Y.-S., Tan, K.H., Yap, F., 2018a. Oral processing behaviours that promote children's energy intake are associated with parent-reported appetitive traits: results from the GUSTO cohort. Appetite 126, 8−15.

Fogel, A., Mccrickerd, K., Fries, L.R., Goh, A.T., Quah, P.L., Chan, M.J., Toh, J.Y., Chong, Y.-S., Tan, K.H., Yap, F., 2018b. Eating in the absence of hunger: stability over time and associations with eating behaviours and body composition in children. Physiol. Behav. 192, 82−89.

Fogel, A., Fries, L.R., Mccrickerd, K., Goh, A.T., Chan, M.J., Toh, J.Y., Chong, Y.S., Tan, K.H., Yap, F., Shek, L.P., 2019a. Prospective associations between parental feeding practices and children's oral processing behaviours. Mater. Child Nutr. 15, e12635.

Fogel, A., Mccrickerd, K., Goh, A.T., Fries, L.R., Chong, Y.-S., Tan, K.H., Yap, F., Shek, L.P., Meaney, M.J., Cai, S., Silveira, P.P., Broekman, B.F.P., Lee, Y.S., Godfrey, K.M., Chong, M.F.F., Forde, C.G., 2019b. Associations between inhibitory control, eating behaviours and adiposity in 6-year-old children. Int. J. Obes. 43, 1344−1353.

Fogel, A., Mccrickerd, K., Aris, I.M., Goh, A.T., Chong, Y.-S., Tan, K.H., Yap, F., Shek, L.P., Meaney, M.J., Broekman, B.F., 2020. Eating behaviors moderate the associations between risk factors in the first 1000 days and adiposity outcomes at 6 years of age. Am. J. Clin. Nutr. 111, 997−1006.

Ford, A.L., Bergh, C., Södersten, P., Sabin, M.A., Hollinghurst, S., Hunt, L.P., Shield, J.P.H., 2010. Treatment of childhood obesity by retraining eating behaviour: randomised controlled trial. Br. Med. J. 340, b5388, 2010;340.

Forde, C.G., Stieger, M., 2022. Chapter 6 metabolic impacts of food oral processing. In: Oral Processing and Consumer Perception: Biophysics, Food Microstructures and Health. The Royal Society of Chemistry.

Forde, C.G., Bolhuis, D., Thaler, T., Graaf, C.D., Martin, N., 2013a. Influence of meal texture on eating rate and food intake. Results from three ad-libitum trials. Appetite 71, 474.

Forde, C.G., Van Kuijk, N., Thaler, T., De Graaf, C., Martin, N., 2013b. Oral processing characteristics of solid savoury meal components, and relationship with food composition, sensory attributes and expected satiation. Appetite 60, 208−219.

Forde, C.G., Van Kuijk, N., Thaler, T., De Graaf, C., Martin, N., 2013c. Texture and savoury taste influences on food intake in a realistic hot lunch time meal. Appetite 60, 180−186.

Forde, C.G., Almiron-Roig, E., Brunstrom, J.M., 2015. Expected satiety: application to weight management and understanding energy selection in humans. Curr. Obes. Rep. 4, 131−140.

Forde, C., Leong, C., Chia-Ming, E., Mccrickerd, K., 2017. Fast or slow-foods? Describing natural variations in oral processing characteristics across a wide range of Asian foods. Food Funct. 8, 595−606.

Forde, C.G., Fogel, A., Mccrickerd, K., 2019. Children's Eating Behaviors and Energy Intake: Overlapping Influences and Opportunities for Intervention. Nurturing a Healthy Generation of Children: Research Gaps and Opportunities NNI96. Karger Publishers.

Forde, C.G., Mars, M., De Graaf, K., 2020. Ultra-processing or oral processing? A role for energy density and eating rate in moderating energy intake from processed foods. Curr. Develop. Nutrit. 4, nzaa019.

Forde, C.G., 2016. Flavour perception and satiation. In: Eteviant, P., Salle, C., Guichard, E., Voilley, A. (Eds.), Flavour; from Food to Behaviour, Well-Being and Health, second ed. Woodhead Publishing, pp. 251−276.

Forde, C., 2018a. From perception to ingestion; the role of sensory properties in energy selection, eating behaviour and food intake. Food Qual. Prefer. 66, 171−177.

Forde, C.G., 2018b. Measuring Satiation and Satiety. Methods in Consumer Research, Vol. 2. Elsevier.

Forestell, C.A., Mennella, J.A., 2015. The ontogeny of taste perception and preference throughout childhood. Handb. Olfact. Gustat. 12, 795−828.

Fuke, S., Shimizu, T., 1993. Sensory and preference aspects of umami. Trend. Food Sci. Technol. 4, 246−251.

Gaillet, M., Sulmont-Rossé, C., Issanchou, S., Chabanet, C., Chambaron, S., 2013. Priming effects of an olfactory food cue on subsequent food-related behaviour. Food Qual. Prefer. 30, 274−281.

Gaillet-Torrent, M., Sulmont-Rossé, C., Issanchou, S., Chabanet, C., Chambaron, S., 2014. Impact of a non-attentively perceived odour on subsequent food choices. Appetite 76, 17−22.

Gierczynski, I., Guichard, E., Laboure, H., 2011. Aroma perception in dairy products: the roles of texture, aroma release and consumer physiology. A review. Flav. Frag. J. 26, 141−152.

Goh, A.T., Choy, J.Y.M., Chua, X.H., Ponnalagu, S., Khoo, C.M., Whitton, C., Van Dam, R.M., Forde, C.G., 2020. Increased oral processing and a slower eating rate increase glycaemic, insulin and satiety responses to a mixed meal tolerance test. Eur. J. Nutr. 1−15.

Goh, A.T., Chatonidi, G., Choy, M., Ponnalagu, S., Stieger, M., Forde, C.G., 2021. Impact of individual differences in eating rate on oral processing, bolus properties and post-meal glucose responses. Physiol. Behav. 113495.

Gosby, A.K., Conigrave, A.D., Lau, N.S., Iglesias, M.A., Hall, R.M., Jebb, S.A., Brand-Miller, J., Caterson, I.D., Raubenheimer, D., Simpson, S.J., 2011. Testing protein leverage in lean humans: a randomised controlled experimental study. PLoS One 6, e25929.

Griffioen-Roose, S., Mars, M., Finlayson, G., Blundell, J.E., De Graaf, C., 2009. Satiation due to equally palatable sweet and savory meals does not differ in normal weight young adults. J. Nutr. 139, 2093−2098.

Griffioen-Roose, S., Hogenkamp, P.S., Mars, M., Finlayson, G., De Graaf, C., 2012a. Taste of a 24-h diet and its effect on subsequent food preferences and satiety. Appetite 59, 1−8.

Griffioen-Roose, S., Mars, M., Siebelink, E., Finlayson, G., Tomé, D., De Graaf, C., 2012b. Protein status elicits compensatory changes in food intake and food preferences. Am. J. Clin. Nutr. 95, 32−38.

Hall, K.D., Ayuketah, A., Brychta, R., Cai, H., Cassimatis, T., Chen, K.Y., Chung, S.T., Costa, E., Courville, A., Darcey, V., 2019. Ultra-processed diets cause excess calorie intake and weight gain: an inpatient randomized controlled trial of ad libitum food intake. Cell Metab. 30, 67−77.

Harmon, C.P., Deng, D., Breslin, P.A., 2021. Bitter taste receptors (T2Rs) are sentinels that coordinate metabolic and immunological defense responses. Curr. Opin. Physiol. 20, 70−76.

Harrison, D., Stevens, B., Bueno, M., Yamada, J., Adams-Webber, T., Beyene, J., Ohlsson, A., 2010. Efficacy of sweet solutions for analgesia in infants between 1 and 12 months of age: a systematic review. Archiv. Dis. Child. 95, 406−413.

Härtel, B., Graubaum, H., Schneider, B., 1993. The influence of sweetener solutions on the secretion of insulin and the blood glucose level. Ernährungsumschau 40, 152−155.

Hayabuchi, H., Morita, R., Ohta, M., Nanri, A., Matsumoto, H., Fujitani, S., Yoshida, S., Ito, S., Sakima, A., Takase, H., 2020. Validation of preferred salt concentration in soup based on a randomized blinded experiment in multiple regions in Japan—influence of umami (L-glutamate) on saltiness and palatability of low-salt solutions. Hypertens. Res. 43, 525−533.

Henry, C.J., Ponnalagu, S., Bi, X., Forde, C., 2018. Does basal metabolic rate drive eating rate? Physiol. Behav. 189, 74−77.

Herz, R.S., Von Clef, J., 2001. The influence of verbal labeling on the perception of odors: evidence for olfactory illusions? Perception 30, 381−391.

Hollis, J.H., Henry, C.J.K., 2007. Sensory-specific satiety and flavor amplification of foods. J. Sens. Stud. 22, 367−376.

Hollis, J.H., 2018. The effect of mastication on food intake, satiety and body weight. Physiol. Behav. 193, 242−245.

Hutchings, J.B., Lillford, P.J., 1988. The perception of food texture - the philosophy of the breakdown path. J. Text. Stud. 19, 103−115.

Hyseni, L., Elliot-Green, A., Lloyd-Williams, F., Kypridemos, C., O'flaherty, M., Mcgill, R., Orton, L., Bromley, H., Cappuccio, F.P., Capewell, S., 2017. Systematic review of dietary salt reduction policies: evidence for an effectiveness hierarchy? PLoS One 12, e0177535.

Imada, T., Hao, S.S., Torii, K., Kimura, E., 2014. Supplementing chicken broth with monosodium glutamate reduces energy intake from high fat and sweet snacks in middle-aged healthy women. Appetite 79, 158−165.

Jasper, P.W., James, M.T., Hoover, A.W., Muth, E.R., 2016. Effects of bite count feedback from a wearable device and goal setting on consumption in young adults. J. Acad. Nutr. Dietet. 116, 1785−1793.

Kang, M., Joo, M., Hong, H., Kang, H., 2021. Eating speed, physical activity, and cardiorespiratory fitness are independent predictors of metabolic syndrome in Korean university students. Nutrients 13, 2420.

Katsuyuki, A., 2020. Umami and salt reduction. Hypertens. Res. 43, 569−570.

Keast, R.S.J., Costanzo, A., 2015. Is fat the sixth taste primary? Evidence and implications. Flavour 4, 1−7.

Kern, D.L., Mcphee, L., Fisher, J., Johnson, S., Birch, L.L., 1993. The postingestive consequences of fat condition preferences for flavors associated with high dietary fat. Physiol. Behav. 54, 71−76.

Kilcast, D., Lewis, D.F., 1990. Structure and texture—their importance in food quality. Nutr. Bull. 15, 103−113.

Lasschuijt, M.P., Brouwer-Brolsma, E., Mars, M., Siebelink, E., Feskens, E., De Graaf, C., Camps, G., 2021. Concept development and use of an automated food intake and eating behavior assessment method. J. Visual. Exper. 168, e62144.

Lease, H., Hendrie, G.A., Poelman, A.A.M., Delahunty, C., Cox, D.N., 2016. A Sensory-Diet database: a tool to characterise the sensory qualities of diets. Food Qual. Prefer. 49, 20−32.

Leshem, M., 2009. Biobehavior of the human love of salt. Neurosci. Biobehav. Rev. 33, 1−17.

Leshem, M., 2020. Salt need needs investigation. Br. J. Nutr. 123, 1312−1320.

Lieberman, H.R., Fulgoni Iii, V.L., Agarwal, S., Pasiakos, S.M., Berryman, C.E., 2020. Protein intake is more stable than carbohydrate or fat intake across various US demographic groups and international populations. Am. J. Clin. Nutr. 112, 180−186.

Liem, D.G., Mennella, J.A., 2002. Sweet and sour preferences during childhood: role of early experiences. Dev. Psychobiol. 41, 388−395.

Liem, D.G., Russell, C.G., 2019. Supersize me. Serving carrots whole versus diced influences children’s consumption. Food Qual. Prefer. 74, 30−37.

Liem, D.G., Westerbeek, A., Wolterink, S., Kok, F.J., De Graaf, C., 2004. Sour taste preferences of children relate to preference for novel and intense stimuli. Chem. Sens. 29, 713−720.

Liu, D., Archer, N., Duesing, K., Hannan, G., Keast, R., 2016. Mechanism of fat taste perception: association with diet and obesity. Prog. Lipid Res. 63, 41−49.

Llewellyn, C.H., Van Jaarsveld, C.H., Boniface, D., Carnell, S., Wardle, J., 2008. Eating rate is a heritable phenotype related to weight in children. Am. J. Clin. Nutr. 88, 1560−1566.

Llewellyn, C.H., Trzaskowski, M., Van Jaarsveld, C.H., Plomin, R., Wardle, J., 2014. Satiety mechanisms in genetic risk of obesity. JAMA Pediatr. 168, 338−344.

Mars, M., Hogenkamp, P., Gosses, A., Stafleu, A., De Graaf, C., 2009. Effect of viscosity on learned satiation. Physiol. Behav. 98, 60−66.

Martin, C.K., Williamson, D.A., Geiselman, P.J., Walden, H., Smeets, M., Morales, S., Redmann Jr., S., 2005. Consistency of food intake over four eating sessions in the laboratory. Eat. Behav. 6, 365−372.

Martin, C.K., Anton, S.D., Walden, H., Arnett, C., Greenway, F.L., Williamson, D.A., 2007. Slower eating rate reduces the food intake of men, but not women: implications for behavioral weight control. Behav. Res. Ther. 45, 2349−2359.

Martin, C., Visalli, M., Lange, C., Schlich, P., Issanchou, S., 2014. Creation of a food taste database using an in-home “taste” profile method. Food Qual. Prefer. 36, 70−80.

Marty, L., Bentivegna, H., Nicklaus, S., Monnery-Patris, S., Chambaron, S., 2017. Non-conscious effect of food odors on Children’s food choices varies by weight status. Front. Nutrit. 4, 16.

Masic, U., Yeomans, M.R., 2014. Umami flavor enhances appetite but also increases satiety. Am. J. Clin. Nutr. 100, 532−538.

Masic, U., Yeomans, M.R., 2017. Does acute or habitual protein deprivation influence liking for monosodium glutamate? Physiol. Behav. 171, 79−86.

Mathey, M.-F.A., Siebelink, E., De Graaf, C., Van Staveren, W.A., 2001. Flavor enhancement of food improves dietary intake and nutritional status of elderly nursing home residents. J. Gerontol. Ser A Biol. Sci. Med. Sci. 56, M200−M205.

Mattes, R.D., 2009. Oral fat exposure pattern and lipid loading effects on the serum triacylglycerol concentration of humans. Chemosens. Percept. 2, 180−185.

Mattes, R.D., 2021. Taste, teleology and macronutrient intake. Curr. Opin. Physiol. 19, 162−167.

Mccrickerd, K., Forde, C., 2016. Sensory influences on food intake control: moving beyond palatability. Obes. Rev. 17, 18−29.

Mccrickerd, K., Forde, C.G., 2017. Consistency of eating rate, oral processing behaviours and energy intake across meals. Nutrients 9.

Mccrickerd, K., Fogel, A., Goh, A., Forde, C.G., 2017a. Faster eating rates are stable over time and predict prospective increases in fat mass; Results from the GUSTO Cohort. In: Presentation at the 25th Annual Society for the Study of Ingestive Behaviour Meeting, Montreal, 18-22nd of July.

Mccrickerd, K., Lim, C.M., Leong, C., Chia, E.M., Forde, C.G., 2017b. Texture-based differences in eating rate reduce the impact of increased energy density and large portions on meal size in adults. J. Nutr. 147, 1208−1217.

Meilgaard, M.C., Civille, G.V., Carr, B.T. (2007). Sensory evaluation techniques, fourth ed. MI: CRC Press.

Methven, L., Allen, V.J., Withers, C.A., Gosney, M.A., 2012. Ageing and taste. Proc. Nutr. Soc. 71, 556−565.

Miyaki, T., Imada, T., Shuzhen Hao, S., Kimura, E., 2016. Monosodium l-glutamate in soup reduces subsequent energy intake from high-fat savoury food in overweight and obese women. Br. J. Nutr. 115, 176−184.

Morquecho-Campos, P., Bikker, F.J., Nazmi, K., De Graaf, K., Laine, M.L., Boesveldt, S., 2019. Impact of food odors signaling specific taste qualities and macronutrient content on saliva secretion and composition. Appetite 143, 104399.

Morquecho-Campos, P., De Graaf, K., Boesveldt, S., 2020. Smelling our appetite? The influence of food odors on congruent appetite, food preferences and intake. Food Qual. Prefer. 85, 103959.

Neyraud, E., Heinzerling, C., Bult, J., Mesmin, C., Dransfield, E., 2009. Effects of different tastants on parotid saliva flow and composition. Chemosens. Percept. 2, 108−116.

Nor, N.D.M., Houston-Price, C., Harvey, K., Methven, L., 2021. The effects of taste sensitivity and repeated taste exposure on children's intake and liking of turnip (Brassica rapa subsp. rapa); a bitter Brassica vegetable. Appetite 157, 104991.

Ohkuma, T., Hirakawa, Y., Nakamura, U., Kiyohara, Y., Kitazono, T., Ninomiya, T., 2015. Association between eating rate and obesity: a systematic review and meta-analysis. Int. J. Obes. 39, 1589−1596.

Paravisini, L., Guichard, E., 2016. Interactions between aroma compounds and food matrix. In: Guichard, E., Salles, C., Morzel, M., Le Bon, A.-M. (Eds.), Flavour: From Food to Perception. John Wiley & Sons, Inc., Chichester, West Sussex, USA, pp. 208−234.

Peng, M., Coutts, D., Wang, T., Cakmak, Y.O., 2019. Systematic review of olfactory shifts related to obesity. Obes. Rev. 20, 325−338.

Pepino, M.Y., 2015. Metabolic effects of non-nutritive sweeteners. Physiol. Behav. 152, 450−455. Part B.

Plug, H., Haring, P., 1993. The role of ingredient-flavour interactions in the development of fat-free foods. Trend. Food Sci. Technol. 4, 150−152.

Poessel, M., Breuer, N., Joshi, A., Pampel, A., Villringer, A., Hummel, T., Horstmann, A., 2020a. Reduced olfactory bulb volume in obesity and its relation to metabolic health status. Front. Hum. Neurosci. 14, 515.

Poessel, M., Freiherr, J., Wiencke, K., Villringer, A., Horstmann, A., 2020b. Insulin resistance is associated with reduced food odor sensitivity across a wide range of body weights. Nutrients 12, 2201.

Poessel, M., Morys, F., Breuer, N., Villringer, A., Hummel, T., Horstmann, A., 2022. Brain response to food odors is not associated with body mass index and obesity-related metabolic health measures. Appetite 168, 105774.

Polycarpe, E., Arnould, L., Schmitt, E., Duvillard, L., Ferrant, E., Isambert, N., Duvillard, C., Beltramo, J.L., Chevet, D., Chauffert, B., 2004. Low urine osmolarity as a determinant of cisplatin-induced nephrotoxicity. Int. J. Canc. 111, 131−137.

Postma, E., De Graaf, C., Boesveldt, S., 2020. Food preferences and intake in a population of Dutch individuals with self-reported smell loss: an online survey. Food Qual. Prefer. 79, 103771.

Proserpio, C., De Graaf, C., Laureati, M., Pagliarini, E., Boesveldt, S., 2017. Impact of ambient odors on food intake, saliva production and appetite ratings. Physiol. Behav. 174, 35−41.

Proserpio, C., Invitti, C., Boesveldt, S., Pasqualinotto, L., Laureati, M., Cattaneo, C., Pagliarini, E., 2019. Ambient odor exposure affects food intake and sensory specific appetite in obese women. Front. Psychol. 10, 7.

Quah, P.L., Ginanjar, S., Fries, L.R., Fogel, A., Mccrickerd, K., Goh, A.T., Chan, M.J., Lim, H.X., Toh, J.Y., Aris, I.M., Lee, Y.S., Pang, W.W., Basnyat, I., Yap, F., Godfrey, K.M., Gluckman, P., Chong, Y.S., Shek, P.C.L., Tan, K.H., Forde, C.G., Chong, M.F.F., 2019. Longitudinal analysis between maternal feeding practices and body mass index (BMI): a study in asian Singaporean preschoolers. Front. Nutrit. 6.

Ramaekers, M.G., Boesveldt, S., Gort, G., Lakemond, C.M.M., Van Boekel, M.A.J.S., Luning, P.A., 2014a. Sensory-specific appetite is affected by actively smelled food odors and remains stable over time in normal-weight women. J. Nutr. 144.

Ramaekers, M.G., Boesveldt, S., Lakemond, C.M.M., Van Boekel, M.A.J.S., Luning, P.A., 2014b. Odors: appetizing or satiating? Development of appetite during odor exposure over time. Int. J. Obes. 38, 650−656.

Relkin, P., Fabre, M., Guichard, E., 2004. Effect of fat nature and aroma compound hydrophobicity on flavor release from complex food emulsions. J. Agric. Food Chem. 52, 6257−6263.

Rezaie, P., Bitarafan, V., Horowitz, M., Feinle-Bisset, C., 2021. Effects of bitter substances on GI function, energy intake and glycaemia-do preclinical findings translate to outcomes in humans? Nutrients 13, 1317.

Robinson, E., Almiron-Roig, E., Rutters, F., De Graaf, C., Forde, C.G., Tudur Smith, C., Nolan, S.J., Jebb, S.A., 2014. A systematic review and meta-analysis examining the effect of eating rate on energy intake and hunger. Am. J. Clin. Nutr. 100, 123−151.

Rogers, P., Hogenkamp, P., De Graaf, C., Higgs, S., Lluch, A., Ness, A., Penfold, C., Perry, R., Putz, P., Yeomans, M., 2016. Does low-energy sweetener consumption affect energy intake and body weight? A systematic review, including meta-analyses, of the evidence from human and animal studies. Int. J. Obes. 40, 381−394.

Rozin, P., Vollmecke, T.A., 1986. Food likes and dislikes. Annu. Rev. Nutr. 6, 433−456.

Ruijschop, R.M., Boelrijk, A.E., De Ru, J.A., De Graaf, C., Westerterp-Plantenga, M.S., 2008a. Effects of retro-nasal aroma release on satiation. Br. J. Nutr. 99, 1140−1148.

Ruijschop, R.M.A.J., Boelrijk, A.E.M., Te Giffel, M.C., 2008b. Satiety effects of a dairy beverage fermented with propionic acid bacteria. Int. Dairy J. 18, 945−950.

Ruijschop, R.M., Burgering, M.J., Jacobs, M.A., Boelrijk, A.E., 2009a. Retro-nasal aroma release depends on both subject and product differences: a link to food intake regulation? Chem. Sens. 34, 395−403.

Ruijschop, R.M.A.J., Boelrijk, A.E., De Graaf, C., Westerterp-Plantenga, M.S., 2009b. Retronasal aroma release and satiation: a review. J. Agric. Food Chem. 57, 9888−9894.

Ruijschop, R.M.A.J., Boelrijk, A.E.M., Te Giffel, M.C., De Graaf, C., Westerterp-Plantenga, M.S., 2009c. Induction of satiation via aroma in dairy products. Aust. J. Dairy Technol. 64, 50−53.

Ruijschop, R.M.A.J., Boelrijk, A.E., Burgering, M.J., De Graaf, C., Westerterp-Plantenga, M.S., 2010. Acute effects of complexity in aroma composition on satiation and food intake. Chem. Sens. 35, 91−100.

Running, C.A., Craig, B.A., Mattes, R.D., 2015. Oleogustus: the unique taste of fat. Chem. Sens. 40, 507−516.

Salles, C., 2021. Acids in Foods and Perception of Sourness. In: Lavelle, C., This, H. (Eds.), Handbook of Molecular Gastronomy, CRC Press, Boca Raton, FL, pp. 7−12.

Simpson, S.J., Raubenheimer, D., 2005. Obesity: the protein leverage hypothesis. Obes. Rev. 6, 133−142.

Stewart, J.E., Feinle-Bisset, C., Golding, M., Delahunty, C., Clifton, P.M., Keast, R.S.J., 2010. Oral sensitivity to fatty acids, food consumption and BMI in human subjects. Br. J. Nutr. 104, 145−152.

Stewart, J.E., Newman, L.P., Keast, R.S., 2011. Oral sensitivity to oleic acid is associated with fat intake and body mass index. Clin. Nutr. 30, 838−844.

Stoner, L., Castro, N., Kucharska-Newton, A., Smith-Ryan, A.E., Lark, S., Williams, M.A., Faulkner, J., Skidmore, P., 2019. Food consumption patterns and body composition in children: moderating effects of prop taster status. Nutrients 11, 2037.

Sulmont-Rossé, C., Gaillet, M., Raclot, C., Duclos, M., Servelle, M., Chambaron, S., 2018. Impact of olfactory priming on food intake in an Alzheimer's disease unit. J. Alzheimer's Dis. 66, 1497−1506.

Swithers, S.E., Davidson, T.L., 2008. A role for sweet taste: calorie predictive relations in energy regulation by rats. Behav. Neurosci. 122, 161−173.

Swithers, S.E., Martin, A.A., Davidson, T.L., 2010. High-intensity sweeteners and energy balance. Physiol. Behav. 100, 55−62.

Szczesniak, A.S., 2002. Texture is a sensory property. Food Qual. Prefer. 13, 215−225.

Tan, V.M.H., Ooi, D.S.Q., Kapur, J., Wu, T., Chan, Y.H., Henry, C.J., Lee, Y.S., 2016. The role of digestive factors in determining glycemic response in a multiethnic Asian population. Eur. J. Nutr. 55, 1573−1581.

Tang, C.S., Tan, V.W., Teo, P.S., Forde, C.G., 2020. Savoury and kokumi enhancement increases perceived calories and expectations of fullness in equicaloric beef broths. Food Qual. Prefer. 83, 103897.

Teff, K.L., Devine, J., Engelman, K., 1995. Sweet taste: effect on cephalic phase insulin release in men. Physiol. Behav. 57, 1089−1095.

Teo, P.S., Forde, C.G., 2020. The Impact of Eating Rate on Energy Intake, Body Composition, and Health. Handbook of Eating and Drinking: Interdisciplinary Perspectives, pp. 715−740.

Teo, P.S., Van Langeveld, A.W., Pol, K., Siebelink, E., De Graaf, C., Martin, C., Issanchou, S., Yan, S.W., Mars, M., 2018. Training of a Dutch and Malaysian sensory panel to assess intensities of basic tastes and fat sensation of commonly consumed foods. Food Qual. Prefer. 65, 49−59.

Teo, P.S., Van Dam, R.M., Forde, C.G., 2020a. Combined impact of a faster self-reported eating rate and higher dietary energy intake rate on energy intake and adiposity. Nutrients 12, 3264.

Teo, P.S., Van Dam, R.M., Whitton, C., Tan, L.W.L., Forde, C.G., 2020b. Association between self-reported eating rate, energy intake, and cardiovascular risk factors in a multi-ethnic asian population. Nutrients 12, 1080.

Teo, P.S., Tso, R., Van Dam, R.M., Forde, C.G., 2021. Taste of modern diets: the impact of food processing on nutrient sensing and dietary energy intake. J. Nutr. 152, 200−210.

Tepper, B.J., Nurse, R.J., 1998. PROP taster status is related to fat perception and preference. Ann. New York Acad. Sci. 855, 802−804.

Tey, S.L., Salleh, N., Henry, C.J., Forde, C.G., 2018. Effects of consuming preloads with different energy density and taste quality on energy intake and postprandial blood glucose. Nutrients 10, 161.

Toews, I., Lohner, S., De Gaudry, D.K., Sommer, H., Meerpohl, J.J., 2019. Association between intake of non-sugar sweeteners and health outcomes: systematic review and meta-analyses of randomised and non-randomised controlled trials and observational studies. Br. Med. J. 364.

Tso, R., Forde, C.G., 2021. Unintended consequences: nutritional impact and potential pitfalls of switching from animal-to plant-based foods. Nutrients 13, 2527.

Tso, R., Lim, A.J., Forde, C.G., 2021. A critical appraisal of the evidence supporting consumer motivations for alternative proteins. Foods 10, 24.

Van Den Boer, J., Werts, M., Siebelink, E., De Graaf, C., Mars, M., 2017a. The availability of slow and fast calories in the Dutch diet: the current situation and opportunities for interventions. Foods 6, 87.

Van Den Boer, J.H., Kranendonk, J., Van De Wiel, A., Feskens, E.J., Geelen, A., Mars, M., 2017b. Self-reported eating rate is associated with weight status in a Dutch population: a validation study and a cross-sectional study. Int. J. Behav. Nutr. Phys. Activ. 14, 121.

Van Eck, A., Wijne, C., Fogliano, V., Stieger, M., Scholten, E., 2019. Shape up! How shape, size and addition of condiments influence eating behavior towards vegetables. Food Funct. 10, 5739−5751.

Van Langeveld, A.W., Gibbons, S., Koelliker, Y., Civille, G.V., De Vries, J.H., De Graaf, C., Mars, M., 2017. The relationship between taste and nutrient content in commercially available foods from the United States. Food Qual. Prefer. 57, 1−7.

Van Langeveld, A.W., Teo, P.S., De Vries, J.H., Feskens, E.J., De Graaf, C., Mars, M., 2018. Dietary taste patterns by sex and weight status in The Netherlands. Br. J. Nutr. 119, 1195−1206.

Van Rossum, C., Buurma-Rethans, E., Dinnissen, C., Beukers, M., Brants, H., Ocké, M., 2020. The Diet of the Dutch: Results of the Dutch National Food Consumption Survey 2012-2016.

Viskaal-Van Dongen, M., Kok, F.J., De Graaf, C., 2011. Eating rate of commonly consumed foods promotes food and energy intake. Appetite 56, 25−31.

Wells, J.C., Davies, P.S., Hopkins, M., Blundell, J.E., 2021. The" drive to eat" hypothesis: energy expenditure and fat-free mass but not adiposity are associated with milk intake and energy intake in 12 week infants. Am. J. Clin. Nutr. 114, 505−514.

Wise, P.M., Nattress, L., Flammer, L.J., Beauchamp, G.K., 2015. Reduced dietary intake of simple sugars alters perceived sweet taste intensity but not perceived pleasantness. Am. J. Clin. Nutr. 103 (1), 50−60.

Witt, T., Stokes, J.R., 2015. Physics of food structure breakdown and bolus formation during oral processing of hard and soft solids. Curr. Opin. Food Sci. 3, 110−117.

Yackinous, C., Guinard, J.-X., 2001. Relation between PROP taster status and fat perception, touch, and olfaction. Physiol. Behav. 72, 427−437.

Yackinous, C.A., Guinard, J.X., 2002. Relation between PROP (6-n-propylthiouracil) taster status, taste anatomy and dietary intake measures for young men and women. Appetite 38, 201−209.

Yeomans, M.R., Jackson, A., Lee, M.D., Nesic, J., Durlach, P.J., 2000. Expression of flavour preferences conditioned by caffeine is dependent on caffeine deprivation state. Psychopharmacology 150, 208−215.

Yeomans, M., Lee, M., Gray, R., French, S., 2001. Effects of test-meal palatability on compensatory eating following disguised fat and carbohydrate preloads. Int. J. Obes. Relat. Metabol. Disord. 25, 1215−1224.

Yeomans, M.R., 1998. Taste, palatability and the control of appetite. Proc. Nutr. Soc. 57, 609−615.

Yeomans, M.R., 2006. The role of learning in development of food preferences. Front. Nutrit. Sci. 3, 93.

Zhang, R., Amft, O., 2017. Monitoring chewing and eating in free-living using smart eyeglasses. IEEE J. Biomed. Health Informat. 22, 23−32.

Zhang, R., Amft, O., 2020. Retrieval and timing performance of chewing-based eating event detection in wearable sensors. Sensors 20, 557.

Zhu, Y., Hollis, J.H., 2014a. Chewing thoroughly reduces eating rate and postprandial food palatability but does not influence meal size in older adults. Physiol. Behav. 123, 62−66.

Zhu, Y., Hollis, J.H., 2014b. Increasing the number of chews before swallowing reduces meal size in normal-weight, overweight, and obese adults. J. Acad. Nutr. Dietet. 114, 926−931.

Zhu, Y., Hsu, W.H., Hollis, J.H., 2013. Increasing the number of masticatory cycles is associated with reduced appetite and altered postprandial plasma concentrations of gut hormones, insulin and glucose. Br. J. Nutr. 110, 384−390.

Zhu, B., Haruyama, Y., Muto, T., Yamazaki, T., 2015. Association between eating speed and metabolic syndrome in a three-year population-based cohort study. J. Epidemiol. JE20140131.

Zijlstra, N., Mars, M., De Wijk, R.A., Westerterp-Plantenga, M.S., De Graaf, C., 2008. The effect of viscosity on ad libitum food intake. Int. J. Obes. 32, 676−683.