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Review

Optimising foods for satiety

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Foods that generate strong satiety sensations have obvious benefits for weight management. This review builds on the understanding that a food's satiating power is dependent on the amount of protein, carbohydrate, fat and fibre it contains by examining evidence that the consumer's sensory and cognitive appraisal of the food is also important. It is concluded that numerous features of a food product can be manipulated to enhance the consumer's experience of satiety but the combination of these features will ultimately determine its effect on appetite control. Taking this integrated approach to satiety will optimise the development of high satiety foods.

Introduction

The alarming rise in global rates of overweight and obesity (Popkin, Adair, & Ng, 2012) does not only have profound implications for health and wellbeing (Dixon, 2010) but also for the environment (Hall, Guo, Dore, & Chow, 2009) and the economy (Yach, Stuckler, & Brownell, 2006). Many people live in an "obesogenic" environment that stimulates appetite and promotes an excessive consumption of calories. Influential factors include the advertising and availability of processed energy dense foods and beverages (Halford, Gillespie, Brown, Pontin, & Dovey, 2004; Hill & Peters, 1998), particularly those eaten outside a meal context (Rolls, Roe, Kral, Meengs, & Wall, 2004), shifts in serving size norms favouring larger portions (Nielsen, 2003; Wansink & Kim, 2005), and the relative cost (£/KJ) and accessibility of an unhealthy diet relative to recommended healthier diets (Drewnowski & Darmon, 2005). Changing the current food environment to be more "leanogenic" requires political and cultural reform, with considerable support from the food industry. There is no magic bullet. A pragmatic approach is to make numerous small changes to the food environment to help people eat more healthily. Enhanced satiety foods (those with an increased capacity to inhibit appetite in the period *after* consumption) could be part of this approach, because they directly promote reduced food intake and also aid compliance with healthy eating and weight management strategies, by lessening the effect of sensations of hunger on motivation and mood (Hetherington *et al.*, 2013).

In recent years the food market has seen a rise in the sale of enhanced satiety products (categorically different to reduced-energy diet foods), which claim to be effective at staving off hunger and seem to be well received by the public (Bilman, Kleef, Mela, Hulshof, & van Trijp, 2012; Hetherington *et al.*, 2013). In the UK these are required to abide by European Commission regulation that satiety claims should be substantiated by scientific evidence based on the nutritional profile of the food and not mislead the consumer (European Commission, 2007; 2012). Though there is continued debate about what constitutes a valid claim (Blundell, 2010; Booth & Nouwen, 2010; de Graaf, 2011a, 2011b; Griffioen-Roose, Wanders, & Bánáti, 2013), the vast majority of satiety claim submissions to the European Food Safety Authority (EFSA) fail to be approved because of a lack of evidence that satiety generated by the product leads to reductions in energy intake, and/or that the effect is sustained with repeat experience (Halford & Harrold, 2012).

Despite important scientific advances in understanding the relationship between specific nutrients and appetite control, with some success in the application of these findings to the manufacture of high satiety foods, non-nutrient contributors to the consumer's experience of satiety have received less attention. The purpose of this paper is to discuss what is known about the satiating constituents of food and build on this by examining evidence that contextual cues from cognitive and sensory signals generated at the time of consumption influence the consumer's experience of satiety and also, critically, moderate nutrient-based satiety. Taking this integrated approach to satiety will better inform the development of enhanced satiety

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food products by highlighting the numerous elements of a food that can be manipulated to optimise its affect on appetite, and by demonstrating that the combination of these elements will ultimately determine how effective it is at generating sensations of satiety.

Satiety as a multi-factor construct

The idea that the sensation of satiety is dependent on more than just the metabolic effects of nutrients in the gut and intestine was conceptualised by John Blundell, Rogers, and Hill (1987) over 25 years ago. Their satiety cascade model (Fig. 1), which has been well described in several other reviews (*e.g.* Halford & Harrold, 2012; Van Kleef, Van Trijp, Van Den Borne, & Zondervan, 2012), proposes that even before food arrives in the gut, cognitive and sensory signals generated by the sight and smell of food, and by the oro-sensory experience of food in the oral cavity will influence not only how much is eaten at that eating episode (satiation) but also in the period after consumption. These early satiety signals will integrate with post-ingestive and post-absorptive signals to determine satiety. Pre-ingestive sensory and cognitive signals signify the imminent arrival of a nutrient load, and the body's rapid response to this information is to physiologically prepare for the efficient digestion, absorption and metabolism of nutrients (Pavlov & Thompson, 1902). These cephalic phase responses, involving gastrointestinal hormones, acid secretions and changes to gastric and intestinal motility (see Power & Schulkin, 2008) are thought to heighten post-consumption sensations of satiety because they change how well nutrients are processed by the digestive system (Smeets, Erkner, & De Graaf, 2010). Another way that pre- and post-ingestive signals might interact is through the memory of food consumption; strong pre-ingestive cues might enhance eating encoding and this might impact on the way consumer's interpret physiologically derived satiety sensations, though this is yet to be empirically tested. Either way, it can be predicted that a nutritionally rich food will have maximal impact on appetite only when the experience of consuming it leads the consumer to anticipate its satiating effects. Equally, the same nutrient rich food may have weak effects on satiety if expectations are not in line with its nutrient content. Indeed, when food is ingested in the absence of cognitive and sensory pre-ingestive signalling, for example when delivered directly to the gut via a nasogastric tube, satiety responses to nutrients are weaker (Cecil, Castiglione, French, Francis, & Read, 1998a; Cecil, Francis, & Read, 1998b; Lavin, French, Ruxton, & Read, 2002).

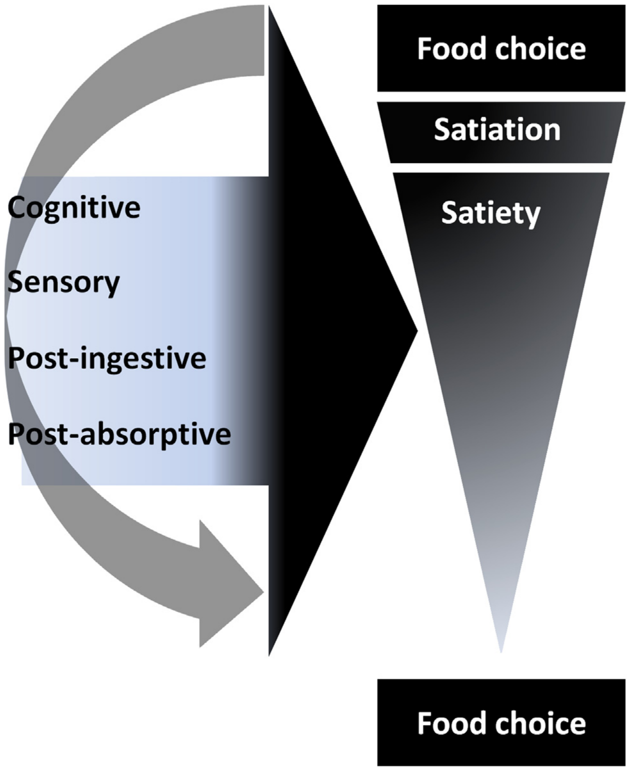

Fig. 1. The satiety cascade. Adapted from Blundell *et al.* (1987).

Food macronutrients and satiety

Classic satiety research has typically looked at the physiological effects of food ingredients in isolation while holding all other contributors to satiety constant. This important work has highlighted that two foods of equal energy may have distinct effects on satiety if their macronutrient compositions differ. For example, women whose diet was modified to be high in protein and carbohydrate for a day reported higher levels of satiety compared to another day when the principle energy source of their diet was fat, despite the diets being matched for energy content (Westerterp-Plantenga, Rolland, Wilson, & Westerterp, 1999). The idea of a hierarchy of satiating effects of macronutrients in the order of protein > carbohydrate > fat (Blundell & Macdiarmid, 1997) goes some way to explain why not all calories will have the same impact on satiety, and has been hugely influential in the development of enhanced satiety foods. Nowadays, for many people, "high protein" is synonymous with feeling full and is central to most satiety claims in the appetite management food market. Protein has taken centre stage as *the* high satiety food constitute because of considerable experimental and real-world research indicating that increasing the protein composition of the diet without changing net energy can lead to enhanced feelings of satiety (Paddon-Jones *et al.*, 2008). Possible physiological mechanisms underlying this effect include diet induced thermogenesis (Halton & Hu, 2004) and gastrointestinal hormonal signalling (Veldhorst *et al.*, 2008), while two recent studies indicated that the sensory experience of ingesting protein is also important (Bertenshaw, Lluch, & Yeomans, 2013; Masic & Yeomans, 2013). Randomized trials of high protein diets on weight management provide evidence that these types of eating plans can support longer-term weight loss (*e.g.*

Leidy, Carnell, Mattes, & Campbell, 2007; Skov, Toubro, Rønn, Holm, & Astrup, 1999; Weigle *et al.*, 2005) and potentially aid future weight maintenance (Due, Toubro, Skov, & Astrup, 2004; Westerterp-Plantenga, Lejeune, Nijs, Van Ooijen, & Kovacs, 2004). In the laboratory the satiating effects of high protein foods or meals have been compared to iso-energetic lower protein counterparts, typically using "preload" methodology where the measure of satiety is post-consumption subjective ratings of appetite and/or food intake. The majority of these types of studies indicate that high protein foods deliver better satiety than energy matched foods with lower levels of protein (*e.g.* Astbury, Stevenson, Morris, Taylor, & Macdonald, 2010; Bertenshaw, Lluch, & Yeomans, 2009; Booth, Chase, & Campbell, 1970; Fischer, Colombani, & Wenk, 2004; Hill & Blundell, 1986; Rolls, Hetherington, & Burley, 1988; Teff, Young, & Blundell, 1989), though this not always reported (de Graaf, Hulshof, Weststrate, & Jas, 1992; Vozzo *et al.*, 2003). Overall this body of literature indicates that increasing the protein content of a food is an effective way to deliver enhanced satiety to the consumer, but manipulating the macronutrient content of a food while keeping energy constant means it is difficult to be certain whether these effects are due to the superior satiating effect of protein, the reduction of less satiating nutrients carbohydrate and fat, or a combination of both of these. Moreover, it is not known whether these effects are maintained after repeat experience; for these reasons EFSA are yet to approve claims based on a general protein effect (European Commission, 2007; 2012).

High protein food products invariably contain other energy-yielding nutrients, usually both carbohydrate and fat. Therefore, in order to optimise high satiety products the carbohydrate-to-fat ratio should also be considered. Protein's position at the top of the satiety hierarchy is fairly well accepted but the order of carbohydrate and fat is often disputed, with this debate further complicated by variability in glycaemic responses to carbohydrate ingestion which can influence satiety signalling (Brand-Miller, Holt, Pawlak, & McMillan, 2002). With regard to satiety, the low-fat rhetoric of recent years seems justified: consuming more energy from carbohydrate than fat has been linked to reduced risk of being overweight or obese (Astrup, Grunwald, Melanson, Saris, & Hill, 2000; Gaesser, 2007), the implication being that high carbohydrate foods are more satiating than those that are high in fat. In free-feeding experiments when people are offered a range of high fat foods they tend to consume more energy than when they are offered high carbohydrate foods (Blundell, Green, & Burley, 1994), a phenomenon termed high fat hyperphagia or passive over consumption (Blundell & Tremblay, 1995). Importantly, this fat-related increased intake of energy does not lead to increased sensations of satiety (Blundell & Macdiarmid, 1997). In the laboratory, studies have found that high fat preloads are less satiating than energy matched high carbohydrate versions (*e.g.* Cotton, Burley, Weststrate, & Bhmdell, 1994; Holt, 1999; Robinson, Gray, Yeomans, & French, 2005), though not in every case (e.g. de Graaf *et al.*, 1992; Rolls *et al.*, 1994). These mixed findings might be due to between study differences in participants characteristics (Chambers & Yeomans, 2011), and preload ingredients (Rolls & Bell, 1999). One particularly important property of fat is that per gram it delivers more than double the energy of carbohydrate and protein. The prevailing view is that fat's high energy density per unit weight largely accounts for its low satiety value (Blundell & Macdiarmid, 1997; Rolls & Bell, 1999). A high fat food will often be smaller in weight (and volume) than a high carbohydrate food of similar energy and this difference may affect the timing of the processing of the nutrients in the gut (Karhunen, Juvonen, Huotari, Purhonen, & Herzig, 2008) and also consumer beliefs about the likely consequence of consuming that food. That is, people tend to believe a small serving of food will not be enough to satisfy their hunger regardless of the energy it contains (Rolls, Drewnowski, & Ledikwe, 2005) and these satiety expectations are thought to play a key role in eating behaviour (Brunstrom, Shakeshaft, & Scott-Samuel, 2008).

Another food ingredient that can have beneficial effects on satiety responses is dietary fibre (Clark & Slavin, 2013; Howarth, Saltzman, & Roberts, 2001; Wanders *et al.*, 2011). Fibre is a complex and varied macronutrient encompassing a range of non-starch polysaccharides (carbohydrates) and lignin (a non-carbohydrate alcohol derivative), which are either soluble or insoluble and fermentable or non-fermentable (Burton-Freeman, 2000). Fibre is thought to affect satiety in many ways, depending on the fibre type, and relating to its ability to bulk foods, increase viscosity, gel in the stomach and ferment in the gut (Slavin & Green, 2007). Describing the effects of each fibre type is beyond the scope of this review. More generally, a fibre-rich diet is thought to promote satiety and weight management because it will contain foods that are low in energy density, such as fruit and vegetables, which when eaten in the same volume as high energy dense foods are equally as satiating but less energetic (Rolls *et al.*, 2005), indicating that the way in which high fibre foods are digested promotes satiety. Indeed, fibre increases gastric distension, slows the rate of gastric emptying and impacts on satiety hormone release; processes associated with heightened sensations of satiety (Wynne, Stanley, McGowan, & Bloom, 2005). Recently, the contribution of fibre viscosity to satiety has received attention. Vuksan *et al.* (2009) tested the effects of three fibres (consumed in 5g portions dissolved in a beverage) that differed only in terms of their ability to thicken liquid and found that only the most viscous fibre reduced intake at the next meal. Similarly, Juvonen *et al.* (2009) examined the effects of an oat-fibre beverage with or without its natural viscosity (achieved by β-glucanase treatment) and found that the higher viscosity beverage slowed gastric emptying and reduced satiety hormone responses compared to the lower viscosity beverage, leading to lower total energy intake over the course of the day. Wanders *et al.*'s (2011) systematic review also found that fibres classified as viscous were more satiating than less viscous fibres. It is not known if the sensory properties or post-ingestive effects of viscous fibres are driving these effects.

Howarth *et al.* (2001) reviewed 38 studies that directly compared the acute effects on satiety of a low fibre food/meal *vs*. a high fibre food/meal of equal fat and energy contents. Their analysis found that 32/38 studies reported a fibre-related increase in satiety, with this being statistically significant in 26/32 of these studies. However, the findings from two more recent systematic reviews were less positive, with one reporting that only 39% of the reviewed studies showed a significant effect of fibre on satiety (Clark & Slavin, 2013) and the other concluding that overall effects of fibre on satiety and body weight were relatively small (Wanders *et al.*, 2011). Despite the evidence that high fibre foods/diets can dull appetite, albeit an effect that might be fairly modest, EFSA have rejected general fibre-based satiety claims because this food component appears in many forms and effects are not sufficiently characterised (EFSA, 2010). Because of the diversity in fibre type and function, and related sensory characteristics, careful consideration must be given to the fibre selected for a high satiety product.

The traditional approach to understanding satiety, – that is, examining the post-ingestive metabolic effects of foods, – indicates that not all energy-yielding nutrients will affect satiety in the same way. This important work suggests that foods might have optimal effects on appetite control when they are high in protein and fibre and contain more carbohydrate than fat. As well as considering post-ingestive influences on satiety this section has touched on aspects of satiety that could be attributed to the consumer's experience of consuming the food before it is processed by the gastrointestinal system. It was noted that protein's effect on satiety might be dependent on its sensory profile; that fat has a low satiety value possibly because satiety expectations of high energy dense foods are low; and that the perceived viscosity of fibre containing beverages might contribute to the consumer's experience of satiety. The next section will consider in detail how these types of pre-ingestive non-nutritive factors may contribute to satiety.

The experience of food consumption and satiety

The taste, smell and texture of a food all contribute to the representation of its flavour, but food texture (or form) has been isolated as a sensory component of food that plays a key role in satiety. This is because orosensory signalling is refined by a lifetime of food experiences, when it is learnt that certain properties of a food's flavour are better predictors of the presence of nutrients than others (Le Magnen, 1955). Viscous foods are invariably nutrient rich and consumed in the context of hunger, unlike fluids that may or may not contain nutrients and are primarily consumed for their thirst-quenching properties. Food texture, therefore, may serve as a reliable predictive cue for future sensations of satiety (Davidson & Swithers, 2005), shaping expectations about the affect a food will have on appetite. Textured foods require mastication which will slow rates of consumption and enhance orosensory exposure time (Zijlstra, Mars, de Wijk, Westerterp-Plantenga, & de Graaf, 2008). The mechanical processing of food in the mouth might be one way in which the nutrient content of a food is estimated. Indeed, chewing has been associated with satiety-related cognitions (Forde, van Kuijk, Thaler, de Graaf, & Martin, 2013), preparatory cephalic phase responses (Li *et al.*, 2011) and appetite peptide release (Katsuragi, Ookuma, Yoshimatsu, Kurokawa, & Sakata, 1994; Li *et al.*; 2011), but relationships with satiety signals are not always reported (Mattes & Considine, 2013; Teff, 2010).

A role for texture in satiety is first evidenced by data indicating that solid and liquid calories affect appetite in distinct ways. In a recent systematic review Almiron-Roig *et al.* (2013) examined how people's ability to compensate for the energy content of a preload varied according to its form. Typically, a compensation score is calculated by measuring reductions in intake at a later test meal(s) and expressing this as a percentage of the preload energy, whereby 100% equals perfect compensation. When participants consumed a liquid preload (*e.g.* fruit juice) their adjusted intake at the next meal compensated for only 71% of the preload energy compared to 95% when the preloads were in semi-solid form (*e.g.* yoghurt) and 109% in solid form (*e.g.* bread), providing evidence that liquid calories have weaker effects on satiety that may lead to excess energy intake. This fits with results from systematic reviews of epidemiological data showing a positive relationship between energy consumed in liquid form and weight gain (Malik, Schulze, & Hu, 2006; Vartanian, Schwartz, & Brownell, 2007).

The effect of food form on satiety has also been examined by manipulating the viscosity of test foods in the laboratory. Findings have been variable (*e.g.* DiMeglio & Mattes, 2000; Russell & Delahunty, 2004; Tsuchiya, Almiron-Roig, Lluch, Guyonnet, & Drewnowski, 2006), perhaps because the high and low viscous comparison foods were poorly matched for other characteristics important to satiety, such as flavour, pleasantness and nutrient content. Studies that have succeeded in matching the comparative test products on dimensions other than viscosity support a role for texture in satiety. For example, increasing the viscosity of a semi-solid chocolate pudding reduced eating rate, changed gastric responses and increased subjective reports of satiety (Zhu, Hsu, & Hollis, 2013), post-consumption hunger was reduced by thickening a “shake” (Mattes & Rothacker, 2001) and enhancing the thickness and creaminess of a yoghurt beverage changed perceptions of how satiating it was likely to be (McCrickerd, Chambers, Brunstrom, & Yeomans, 2012) and reduced subsequent lunch intake (Chambers, Ells, & Yeomans, 2013; Yeomans & Chambers, 2011). It is not possible to be certain that the satiating effects of these viscosity manipulations were solely attributable to sensory signalling because the added thickening agents (fibres) might have influenced satiety by slowing the rate of gastric emptying (Slavin & Green, 2007). However, relatively small amounts of fibres were used to increase the viscosity of the test products in these studies (1.2 g Tara gum in Chambers *et al.*, 2013 and in Yeomans & Chambers, 2011; 0.1 g cellulose in Mattes & Rothacker, 2001; 3.3 g guar gum in Zhu *et al.*, 2013); in studies reporting that fibres influenced post-ingestive signalling much larger portions were consumed (12 g guar gum in French & Read, 1994; 10.5 g wheat-fibre in Weickert *et al.*, 2006). Moreover, evidence is mixed for gastric emptying times varying according to fibre viscosity (Marciani *et al.*, 2000; Wanders *et al.*, 2011) and dilution in the stomach means that differences in oral viscosity may not be reflected in gastrointestinal viscosity. Besides, the *perceived* viscosity of fibrous foods could be critical to their appetite suppressing effect (Juvonen *et al.*, 2009; Vuksan *et al.*, 2009).

The most compelling evidence for a pre-ingestive explanation for the effect of texture on satiety was reported recently by Cassady, Considine, and Mattes (2012). In their elegant study participants consumed a preload on four occasions: on one day they consumed a cherry liquid beverage and with a convincing cover-story they were led to (falsely) believe that this would turn to a gel in their stomach ("liquid—solid"); on another day they consumed the same beverage and were (correctly) told that this would remain a liquid in their stomach ("liquid—liquid"); in the third condition cherry-flavoured gelatine cubes were consumed which they (correctly) believed would turn to liquid in their stomach ("solid—liquid") and in the final condition they consumed the same gelatine cubes and were (incorrectly) informed that they would remain in this form in their stomach ("solid—solid"). Oral exposure time was held constant on all days, and the researchers chose gelatine jelly as the oral solid as this would rapidly liquidise in the stomach once consumed. To ensure that the actual gastric load was exactly matched in all conditions participants consumed capsules of gelatine on sensory "liquid" days and water and maltodextrin on sensory "solid" days. When the sensory experience of the preload was solid ("solid—liquid" and "solid—solid" conditions) ratings of hunger were lower, gastric emptying was slower, insulin and GLP-1 release increased, ghrelin decreased, and subsequent ad libitum food intake lower compared to the days when the sensory experience was liquid. In addition, the false belief that the preload would turn to a solid in the stomach further augmented these satiety responses. These findings provide strong support for satiety enhancing effects of pre-ingestive sensory and cognitive information.

Before food is processed in the mouth other features of a product can change perceptions about its nutrient content and how it might impact on satiety sensations: in Cassady *et al.*'s study (2012) merely the belief that a food would gel in the stomach was enough to alter satiety responses. One realistic way to influence beliefs is through food labels, which provide detailed nutritional information and can sometimes contain explicit messages about the consequences of consuming a product (*e.g.* "fuller for longer") or its satiety-relevant nutritional components (*e.g.* "high protein"). Experimental studies of food labelling provide some evidence that this type of information can not only change how much a person will eat of that product (*e.g.* Roberto, Larsen, Agnew, Baik, & Brownell, 2010) but also their subsequent appetite. For example, lunch intake was higher after consuming a high calorie yoghurt labelled low fat compared to when no information was presented on the yoghurt (Shide & Rolls, 1995); after consuming a beverage presented as a high calorie milkshake participants reported feeling fuller and eating less at a test meal than when this information was not present (Wooley, 1972); and branding a fruit "smoothie" beverage with a high satiety message enhanced subjective reports of fullness and reduced hunger (Fay, Hinton, Rogers, & Brunstrom, 2011). However, several other studies report no effect of labelling on behavioural measures of appetite control (Chambers *et al.*, 2013; Wardle, 1987; Yeomans, Lartamo, Procter, Lee, & Gray, 2001). Naturalistic studies of real-world products might be a better test of labelling effects on appetite behaviour. Despite this, two intriguing recent studies provide evidence that labelling may alter physiological satiety responses: consuming a milkshake labelled as "620-calorie indulgent" resulted in a steeper decline in the hunger stimulating hormone ghrelin than did consuming the same milkshake labelled as "120-calorie sensible" (Crum, Corbin, Brownell, & Salovey, 2011); and activation of brain areas implicated in appetite regulation was dependent on whether a low calorie drink was labelled as a "treat" or "healthy" (Veldhuizen, Nachtigal, Flammer, de Araujo, & Small, 2013).

A number of innovative studies have demonstrated that the perceived size of a food product is also important for satiety. For example, the visual perception of a meal was shown to be important for appetite control in a study where participants dined in complete darkness. The lack of visual cues led them to overeat a "super-sized" meal, underestimate how much they had consumed and despite consuming greater amounts of food they did not report enhanced sensations of satiety (Scheibehenne, Todd, & Wansink, 2010). In another study, incorporating air into a milkshake preload so that its apparent volume was doubled but its energy density unchanged resulted in a 12% reduction in intake at a subsequent meal and lower reports of hunger (Rolls, Bell, & Waugh, 2000). Using a computer based task Brunstrom *et al.* (2008) presented pictures of a range of common foods and measured beliefs about the food's satiety value, they found that satiety expectations were more in line with the perceived volume of the serving of food rather than its energy content. In a follow up study, this group demonstrated that when participants were asked to consume a "smoothie", the amount of fruit they believed it contained influenced expected and actual satiety responses (Brunstrom, Brown, Hinton, Rogers, & Fay, 2011). Perceptions about the weight of a food may also influence satiety related judgements. Making a food container heavier encouraged people to believe that its content was more energy dense and had a greater satiating power than the content of a visually identical but lighter container (Piqueras-Fiszman & Spence, 2012). Modifying how enhanced-satiety food products are packaged might further augment satiety responses, something as simple as segmenting the food into sub-portions can change perceptions of portion size and have beneficial effects on appetite control (Geier, Wansink, & Rozin, 2012), presumably because people believed they were consuming more this way.

This collection of studies indicates that information about the satiating potential of a product is gathered from its labelling, the look and feel of it and perhaps most importantly from the experience of it in the mouth. Nutrients are important for satiety but this pre-ingestive appraisal of a food's satiating power can also change its appetite suppressing effects, though no studies have examined whether these effects on satiety persist with repeat consumption. What is also not clear from the work presented so far is how critical it is that the appearance and flavour of a high satiety food product align with its nutrient content in order to maximise its physiological effects, or whether it is possible to produce an effective high satiety product by merely designing it to look and taste as it if will be satiating even if it is low in energy, – effectively the ultimate weight management product. To answer these questions, studies are needed to specifically test whether the effects of early satiety signals (*i.e.* those generated by the experience of consuming a food) are dependent on later satiety signals (*i.e.* those generate by the nutrient content of the food).

A closer look at the integration of satiety signals

Wooley (1972) was the first to look at the effects of both cognitive and nutrient signals on satiety responses, by manipulating the perceived calorie content and actual energy of a milkshake. However, the study only compared the cognitive and physiological effects: interactive effects were not statistically tested. Shide and Rolls (1995) also compared the effects of manipulating cognitive and physiological satiety signals, but again their study design did not allow interactive effects to be fully explored. Cecil *et al.* (1998b) took a different approach and conducted an elegant infusion study to show that a soup was most satiating when signals were generated at all levels of the gastrointestinal tract (mouth, stomach and small intestine). This collection of research inspired the Ingestive Behaviour Group at the University of Sussex (http://www.sussex.ac.uk/psychology/sibg), who have conducted a series of studies designed to specifically test an integrative model of satiety. The first of these studies by McCrickerd *et al.* (2012) provided the basis for later studies of interactive effects, establishing that beliefs about the satiating power of a beverage are dependent on satiety-relevant taste and texture cues. The thick texture and creamy taste of low and high energy fruit yoghurt beverages were subtly increased in order to orientate consumer perceptions to the presence of nutrients. This produced four sensory versions of the beverage: thin/low-creamy taste; thin/high-creamy taste; thick/low-creamy taste; thick/high-creamy taste. The sensory manipulations were matched across the energy levels. Participants tasted the drinks and the effect of these sensory manipulations on a computer-based test of expected satiety (Brunstrom *et al.*, 2008) was measured. The thicker beverages were perceived to be thicker and creamier and expected to deliver stronger sensations of satiety than the thinner versions, which were also perceived to be less creamy even when presented with the creamy-taste additions. This was irrespective of the beverage's actual energy content and supports the idea that, at the point of consumption, the sensory properties of food influences beliefs about its post-ingestive effects. These data also suggest that thicker texture is a more influential sensory characteristic than creamy-taste alone, which is in line with other recent research identifying that thick and chewy sensory cue are associated with greater expectations of satiation (Forde *et al.*, 2013; Hogenkamp, Mars, Stafleu, & de Graaf, 2012; Hogenkamp, Stafleu, Mars, Brunstrom, & de Graaf, 2011).

How these types of sensory-generated expectations interact with the actual appetite suppressing effects of a food was explored in the next study. Yeomans and Chambers (2011) tested the hypothesis that a beverage with a satiating nutritional profile (high protein) would become more satiating as its sensory properties better predicted the presence of nutrients. The satiating potency of six fruit yoghurt beverages were tested using preload methodology, with beverages being consumed as a mid-morning snack and post-consumption subjective reports of appetite and intake at a two course test lunch serving as the main outcome measures. The beverages were either low or high in energy (78 kcal *vs*. 279 kcal: 201 kcal difference in energy achieved by the addition of 25 g whey protein isolate and 35 g maltodextrin) and presented with increasing levels of thick and creamy sensory characteristics (low sensory; medium sensory; high sensory). The main finding was that the satiating power of the high energy beverage (indexed by test lunch intake: see Fig. 2) was enhanced by making its sensory characteristics more satiety-predictive (thicker and creamier), an effect not observed in the low energy version of the beverage. Furthermore, in the absence of these sensory enhancements (low sensory condition) the high energy beverage was no more satiating than the low energy version, despite

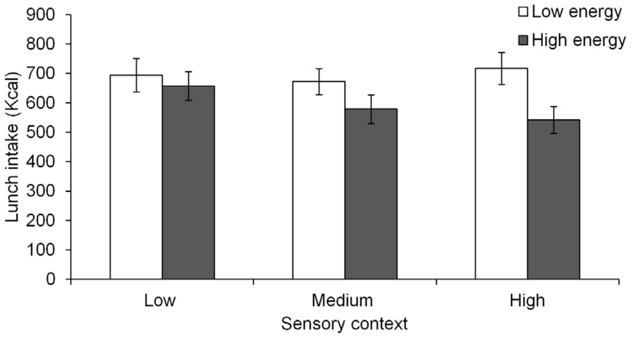

Fig. 2. Mean (±SEM) lunch intake following consumption of a beverage, which was either low or high in energy and presented with low, medium or high levels of thick and creamy sensory characteristics.

providing an additional 201 kcals of energy. Thus the degree to which the beverage suppressed appetite was dependent on its sensory characteristics correctly predicting its nutrient content. Another finding from this study was that participants reported being more hungry before the test lunch when they had consumed the thick and creamy version of the low energy beverage, compared to when they had consumed the same beverage without these sensory enhancements. This "rebound appetite" was unpredicted but might also lend support to an integrative model of satiety: expectations generated by the experience of consuming the thick and creamy but low protein beverage could have triggered anticipatory physiological responses that when unmet by actual nutrients resulted in sensations of hunger.

In parallel with these studies, a similar approach was taken to consider whether the apparent supremacy of protein as a satiating macronutrient might, at least in part, be due to the distinct sensory characteristics of protein-rich foods (Bertenshaw *et al.*, 2013). Again, using a preload design, and building on evidence that protein was more satiating than carbohydrate in a dairy-based drink context (Bertenshaw *et al.*, 2009), it was shown that a carbohydrate-rich drink that had its sensory characterisitics manipluated to match a protein-rich version generated stronger satiety than did a protein-rich drink, which lacked the usual sensory characteristics associated with protein.

These sensory studies provided the first empirical evidence that strengthening satiety expectations generated during the consumption of a food improves the physiological satiating effects of its nutrients. Recent work from Uppsala University (Hogenkamp *et al.*, 2013) and from the University of Sussex (Chambers *et al.*, 2013; McCrickerd, Chambers, & Yeomans, 2014) has used similar methodology to examine whether influencing satiety-related cognitions with labelled information changes satiety responses to nutrient ingestion. Chambers *et al.* (2013) explored this idea by orientating participants to the satiating potency of the test beverage not only by enhancing its thickness and creaminess but also by providing explicit information about its satiating power on the bottle's label. Results indicated that the labelled satiety information had no impact on appetite ratings or test meal intake: only the sensory manipulations enhanced the effect of the high energy beverage's nutrients, while in the low energy beverage they increased appetite, replicating previous findings of sensory-enhanced satiety and rebound appetite (Yeomans & Chambers, 2011). This null effect for labelling was interpreted as evidence that sensory markers of satiety are likely to overshadow any labelling effects. McCrickerd *et al.* (2014) examined these ideas further by comparing the effects on satiety of changing expectations, by either providing addition information on the test product (*e.g.* reduces hunger *vs.* thirst quenching) or by changing its sensory characteristics (thin *vs.* thick). Again, the study was specifically designed to test an integrated model of satiety by examining how these effects depended on the actual nutrient content of the test product. Results support an integrated model of satiety: it was found that providing explicit information that the product would reduce hunger improved the satiating effect of the high energy version of the test product compared to the low energy version. It was also found that improvements in satiety responses were most pronounced when expectations were manipulated via sensory modifications rather than by providing information alone. Hogenkamp *et al.* (2013) also manipulated beliefs about the satiating effect of high and low energy preloads by providing nutritional information and appetite related messages (*e.g.* low in fat and calories *vs.* high fat and calorie-rich) on the products. Results indicated that food intake at a subsequent test meal depended on both the information provided and the energy content of the preload, but that physiological satiety responses were dependent only on the actual nutrient content of the food. Since the satiating effect of the low energy preload was enhanced by informing participants that it was a satiating product, an effect not seen for the high energy product, these findings do not, at first glance, exactly align with those from the University of Sussex. However, the actual energy loads used by Hogenkamp *et al.* were relatively high (low energy 180 kcal *vs.* high energy 530 kcal) with their low energy product containing a physiologically significant amount of nutrients, not dissimilar to calorie content of the high energy test products used at the University of Sussex. Thus, the results from these studies are comparable, when the test products are considered on a calorie content basis. From this collection of studies it might be suggested that real-world food marketing can influence responses to nutrient ingestion, but this is expected to be less effective than optimising the nutrient content and sensory characteristics of a food product for satiety.

An important question for the food industry is how enduring is the sensory enhancement of nutrient-based satiety? Building on the preload methodology used in the initial satiety test of the yoghurt beverages Yeomans *et al.* (2014) examined the effects of repeated consumption of one of four beverages, which were either high or low in energy and with added thick texture and creamy notes (enhanced sensory) or without these sensory manipulations (low sensory). Participants consumed the beverage on seven days with satiety responses measured before repeated exposure (day 1) after five exposure days (day 6), and one month after this exposure period (1 month follow up). When the participants first encountered the beverage their post-consumption subjective ratings of satiety and lunch intake (Fig. 3) were dependent on both the sensory characteristics and energy content of the beverage, with the high energy beverages being more satiating than the low energy versions particularly when it had a thick texture and creamy flavour, replicating previous findings of sensory-enhanced satiety (Bertenshaw *et al.*, 2013; Chambers *et al.*, 2013; Yeomans & Chambers, 2011). Immediately after the exposure phase, and also at the one month follow up, the high energy versions of the beverage remained more satiating than the low energy versions but the sensory manipulations no longer enhanced this effect. This study adds weight to previous evidence indicating that sensory signals generate expectations which assimilate with metabolic nutrient signals to influence satiety, but highlights that this might influence satiety only when foods are first encountered and its satiating effects are unknown. Learning about a food's satiating capacity occurs with repeat exposure (Yeomans, 2012) and so for a familiar product beliefs generated by recent experiences might become more relevant than those generated by the generic satiety-related sensory qualities tested in this study.

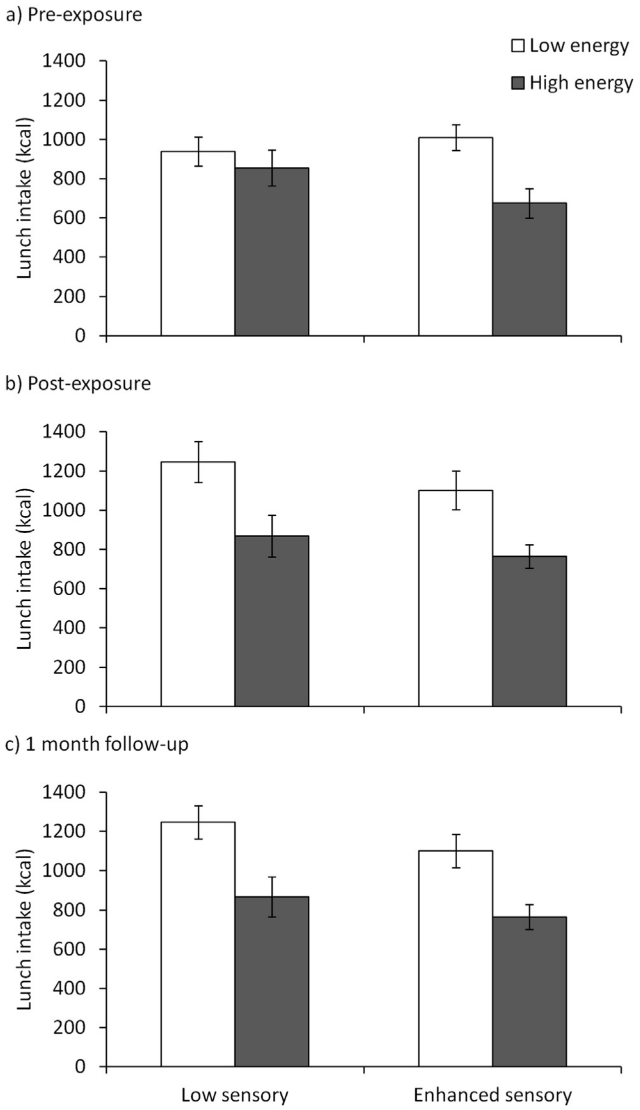

Fig. 3. Mean (±SEM) lunch intake following repeated consumption of a beverage, which was either high or low in energy and with added thick texture and creamy flavour (enhanced sensory) or without these sensory manipulations (low sensory). Lunch intake measured pre-exposure (3a), after five exposure days (3b: post-exposure) and at 1 month follow-up (3c).

This experimental research is only the starting point for understanding how signals arising from cognitive, sensory, gastric and post-gastric processing of food integrate to influence the consumer's experience of satiety. Further work is required to identify whether improvements to the satiating effect of nutrient rich food are 1) achievable in a range of food types other than beverages; 2) effective at modifying appetite control beyond the short-term; 3) evident outside the laboratory in consumers with varying eating habits. Longitudinal real-world studies examining behavioural and biological markers of satiety should be the aim of future research.

Though many questions are still to be answered, this body of work indicates that the appetite suppressing effect of a nutrient rich food can be improved by making small modifications to its sensory profile or by ensuring that consumers are convinced of its satiating effects through product marketing. Critically, this work also indicates that in the absence of these cues a food product designed for satiety might fail to deliver the intended effect. The rebound appetite findings suggest that nutrient light foods that taste as though they will be satiating might actually promote appetite and encourage food intake, thus designing a weight management food product to confer satiety while being low in energy might be unachievable. Finally, it is important to consider that the influence of early satiety signals might diminish as consumers repeatedly experience a food and learn about its physiological significance, though the point at which satiety responses reflect only the nutrient content of food and not the consumer's cognitive and sensory appraisal of it remains to be established.

Conclusions

Satiety research has traditionally centred on the metabolic effects of different food components in the gastrointestinal system. This important work has established that foods high in protein and fibre are particularly effective at generating satiety, due to the breakdown and release of nutrients from these foods, and also hinted that other factors, related to the process of consumption, might contribute to their satiating effect. In the field of psychology it is increasingly recognised that the pre-ingestive appraisal of a food's satiating power, based on its appearance and sensory profile, plays a key role in appetite control, but this has mostly been studied in isolation. The extent to which the satiating capacity of a nutrient rich food is dependent on this evaluation has been the subject of a recent series of studies, mainly from the University of Sussex. This work, based on an integrative model of satiety, provides the first evidence that post-consumption appetite sensations are dependent on congruency between the expected and actual satiating quality of the food, especially the first time it is consumed. In light of these findings, the design of foods maximised for satiety should focus heavily on identifying the optimal combination of satiating nutrients together with a sensory profile and marketing strategy that generates beliefs that the product will be satiating. Attaining support for a satiety claim might be dependent on getting this right. These ideas can also be applied to problems associated with the consumption of energy-yielding beverages, such as sugar-sweetened sodas and beers, which in the UK account for nearly a fifth of our daily energy intake (Ng, Ni Mhurchu, Jebb, & Popkin, 2012). These products are invariably high in energy and often have a very weak effect on satiety. Thus improving their low satiety value might help people avoid excessive intake of calories. When it is not appropriate to change the sensory profile of these types of products, labelled information that draws attention to their impact on appetite rather than thirst could potentially improve their satiating potency (McCrickerd *et al*., 2014). This new body of work also opens up questions about diet foods, by indicating that a food product designed to appear satiating but which is low in actual nutrients can promote appetite. Whether reduced calorie diet foods flavour-matched to their higher calorie counterparts can themselves lead to increased food intake and weight gain is an important question that warrants further investigation. The contribution of factors other than the metabolic effects of nutrients to post-consumption feelings of satiety should not be underestimated; to move satiety research forward future work must adopt an integrated multi-factorial approach.

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