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Eating with our eyes: From visual hunger to digital satiation

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ABSTRACT

One of the brain's key roles is to facilitate foraging and feeding. It is presumably no coincidence, then, that the mouth is situated close to the brain in most animal species. However, the environments in which our brains evolved were far less plentiful in terms of the availability of food resources (i.e., nutriments) than is the case for those of us living in the Western world today. The growing obesity crisis is but one of the signs that humankind is not doing such a great job in terms of optimizing the contemporary food landscape. While the blame here is often put at the doors of the global food companies – offering addictive foods, designed to hit 'the bliss point' in terms of the pleasurable ingredients (sugar, salt, fat, etc.), and the ease of access to calorie-rich foods – we wonder whether there aren't other implicit cues in our environments that might be triggering hunger more often than is perhaps good for us. Here, we take a closer look at the potential role of vision; Specifically, we question the impact that our increasing exposure to images of desirable foods (what is often labelled 'food porn', or 'gastroporn') via digital interfaces might be having, and ask whether it might not inadvertently be exacerbating our desire for food (what we call 'visual hunger'). We review the growing body of cognitive neuroscience research demonstrating the profound effect that viewing such images can have on neural activity, physiological and psychological responses, and visual attention, especially in the 'hungry' brain.

1. Introduction: The brain and food

It was Apicius, the 1st Century Roman gourmand (see Apicius, 1936), who purportedly coined the phrase "*We eat first with our eyes*" (Delwiche, 2012). Nowadays, a growing body of evidence from the cognitive neurosciences is revealing just how true this aphorism really is (e.g., see Van der Laan, De Ridder, Viergever, & Smeets, 2011, for a review). By allowing early life forms to probe and sense their environments at ever greater distances (that is, by allowing them to perceive those stimuli situated in extrapersonal space), eyes, and the visual systems that those eyes feed into, evolved in order to increase a species' chances of survival, by enhancing the efficient detection of energy (food) sources, or nutriments, from within a given environmental niche (e.g., Allman, 2000; Gehring, 2014).

Foraging – the search for nutritious foods – is one of the brain's most important functions. In humans, this activity relies primarily on vision, especially when it comes to finding those foods that we are already familiar with (see also Laska, Freist, & Krause, 2007). In fact, it has been suggested that trichromatic colour vision may originally have developed in primates as an adaptation that facilitated the selection of more energy-rich (and likely red) fruits from in-amongst the dark green forest canopy (e.g., Bompas, Kendall, & Sumner, 2013; Regan et al., 2001; Sumner & Mollon, 2000). Certainly, a complex interplay of animal signalling designed to capture the attention (often visual) of pollinators and/or repel predators has been a central part of the co-evolution of both the visual systems of animals and the colouration schemes utilized in both the animal and plant kingdoms (e.g., see Barth, 1985; Cott, 1940; Poulton, 1890; Rowe & Skelhorn, 2005; Schaefer & Schmidt, 2013).

Finding nutritious sources of food is undoubtedly essential for human well-being, an activity where vision plays a central role, one that is mediated by the attentional, pleasure, and reward systems, as well as by complex physiological cycles of hunger

Abbreviations: SOA, stimulus onset asynchrony; OFC, orbitofrontal cortex; BMI, body-mass index; EFS, external food sensitivity; AR, augmented reality; VR, virtual reality.

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(e.g., Berthoud & Morrison, 2008; Kringelbach, Stein, & van Hartevelt, 2012; LaBar et al., 2001; Masterson, Kirwan, Davidson, & LeCheminant, 2015; Shin, Zheng, & Berthoud, 2009; Van den Bos & de Ridder, 2006). It should come as no surprise, then, that the visual appeal exerts an important influence on the overall pleasure that food elicits (e.g., Hurling & Shepherd, 2003; Spence & Piqueras-Fiszman, 2014).[1]

2. The hungry brain

That the vast majority of animal species have evolved a mouth that is situated close to their brain is presumably no coincidence; As the famous British scientist J.Z. Young (http://en.wikipedia.org/wiki/John_Zachary_Young) once put it: "*The fact that the brain and the mouth are both at the same end of the body may not be as trivial as it seems.*" (Young, 1968, p. 22). In fact, some have taken this observation to suggest that the brain may have evolved in animals as the gut's means of controlling its nutrient intake, and by so doing, increasing the chances of survival and reproduction (e.g., Allman, 2000). Put another way, by determining which nutritious foods to accept (that is, to ingest) and which potentially harmful (e.g., poisonous) foodstuffs to avoid or reject (Piqueras-Fiszman, Kraus, & Spence, 2014), the mouth may ultimately have played an important role in guiding cortical development (e.g., Allman, 2000). Once again, it was J.Z. Young who captured the idea in the opening sentences of one of his papers: "*No animal can live without food. Let us then pursue the corollary of this: Namely, food is about the most important influence in determining the organization of the brain and the behavior that the brain organization dictates.*" (Young, 1968, p. 21).

The brain is the body's most energy-consuming organ, accounting for somewhere in the region of 25% of blood flow, or rather, 25% of the available consumed energy (e.g., see Wenk, 2015, p. 9; Wrangham, 2010). Note that this figure is even higher in the newborn human, where the brain absorbs up to two thirds of the energy that is consumed by the developing organism. As Brown notes: "*In embryos, the first part of the neocortex to develop is the part which will represent the mouth and tongue*..." As the brain grew in size over the course of human evolution, the demands on the visual system to efficiently locate nutrients in the environment would likely also have increased.[2]

It is undoubtedly the case that the food landscapes inhabited by those of us living in the western world today are very different from those that our ancestors had to deal with; In particular, the human brain evolved during a period when food was much scarcer than it is now (Caballero, 2007), and it would appear that our genetic make-up still seemingly drives us toward consumption whenever food is readily accessible (e.g., Marteau, Hollands, & Fletcher, 2012; Pinel, Assanand, & Lehman, 2000; Wenk, 2015). It could well be argued that 'visual hunger' – a concept that we define here as a natural desire, or urge, to look at food – could well be an evolutionary adaption: Our brains learnt to enjoy seeing food, since it would likely precede consumption. The automatic reward associated with the sight of food likely meant another day of sufficient nutrients for survival, and at the same time, the physiological responses would prepare our bodies to receive that food. Our suggestion here is that the regular exposure to virtual foods nowadays, and the array of neural, physiological, and behavioural responses linked to it, might be exacerbating our physiological hunger way too often. Such visual hunger is presumably also part of the reason why various food media have become increasingly successful in this, the digital age.

Before discussing the potential role of visual hunger in public health, we take a brief look at the evidence suggesting that the exposure to appetizing images of food (the majority of which are presented digitally, and hence in a unisensory manner) is becoming an increasingly important source of enjoyment for many people in society today (e.g., see Prince, 2014; Spence, 2015, for a recent commentary). We then take a look at the evidence from the cognitive neurosciences highlighting the effect that viewing food images has on both the physiological and neural levels.

3. Virtual food for hungry eyes

The last 50 years or so have seen a widespread growth in the popularity of various culinary practices, as well as the rise of the celebrity 'chef' (Hansen, 2008). This has led to an inevitable exposure to visually succulent cooking procedures and beautifully-portrayed dishes, often making use of foods that are less than healthy.[3] Every day, it feels as though we are being exposed to ever more appetizing (and typically high calorie) images of food, what some (perhaps pejoratively) call 'gastroporn'[4] or 'food porn' (McBride, 2010; http://en.wikipedia.org/wiki/Food_porn).[5] Moreover, the shelves of the bookstores are increasingly sagging under the weight of all those cookbooks filled with high-definition and digitally-enhanced food images (Spence & Piqueras-Fiszman, 2014; see Myhrvold & Young, 2011, for one particularly spectacular example). It has been suggested that those of us currently living in the Western world are watching more cookery shows on TV than ever before (Bellman, 2004; de Solier, 2005; Prince, 2014; Ray, 2007). Such food shows often glamorize food without necessarily telling a balanced story when it comes to the societal, health, and environmental consequences of excess consumption (Caraher, Lange, & Dixon, 2000; Ketchum, 2005; Meister, 2001). Moreover, the number of hours of TV a person watches is positive correlated with their body-mass index (BMI; see Boulos, Vikre, Oppenheimer, Chang, & Kanarek, 2012).[6] Indeed, laboratory studies have shown that watching food-related TV programs can affect people's patterns of energy intake from a given set of available foods (Bodenlos & Wormuth, 2013). It also leads to an increased consumption of calories in the food that people end

[1] While the appearance of food is not itself a primary reinforcer, food images may acquire such positive properties through Pavlovian-Instrumental Transfer (e.g., see Talmi, Seymour, Dayan, & Dolan, 2008). Note also that the exposure to familiar food images is likely to result in cognitive processes such as the retrieval of relevant memories and hedonic evaluations that have been stored during the previous exposure(s) to, and experiences with, the food in question (e.g., Berthoud & Morrison, 2008; Shin et al., 2009).

[2] Though, of course, mention should also be made here of Wrangham's (2010) intriguing suggestion that the introduction of fire (cooking) would have dramatically increased our ancestors food-related energy efficiency, by allowing them to spend less time foraging, chewing, and digesting. *Homo erectus* would thus have developed a smaller, more efficient digestive tract which would have freed up more energy, thus enabling further brain growth (see also Aiello & Wheeler, 1995).

[3] Howard, Adams, and White (2012) found that TV chefs' recipes were higher in fat, saturated fat, and sodium than recommended by the World Health Organization's nutritional guidelines.

[4] This term, which has now made its way into the Collins English Dictionary, is defined as '*the representation of food in a highly sensual manner*'. The term was first introduced by Alexander Cockburn, in a 1977 article that appeared in the *New York Review of Books*, and was used to emphasize on the visual appearance of food (see Poole, 2012, p. 59).

[5] According to one commentator, the contemporary concern with the presentation of food can be traced back to the early 1970's, with the simultaneous emergence of food photography and food media: "*Really, the concern with how the food looked can be traced back to the emergence of nouvelle cuisine. The pictures of these dishes have set themselves in the mind of the public. Nouvelle cuisine was essentially photogenic*... *Think of the glorious coloured photographs of these dishes, which have become eponymous with the purveying of recipes.*" (Halligan, 1990, p. 121; see also Smart, 1994). In terms of the food porn on TV, Ray (2007) describes it as occurring "*when we imagine cooking and eating while watching other people actually doing it*". Others describe it as 'foodatainment' (Finkelstein, 1999).

[6] Pinel et al. (2000, p. 1112) put it thus: "*From the perspective of our evolutionary analysis, the reason humans living in modern industrialized societies tend to overeat is that the presence, the expectation, or even the thought of food with a high positive-incentive value promotes hunger.*"

up cooking for themselves (Pope, Latimer, & Wansink, 2015), even though many of us are spending less and less time actually interacting with food itself (as the consumption of processed, convenience foods, and ready-meals continues its relentless rise; e.g., Capps, Tedford, & Havlicek, 1985; Hamrick, Andrews, Guthrie, Hopkins, & McClelland, 2011; Howard et al., 2012; Moss, 2013; Smith, Ng, & Popkin, 2013). This is obviously worrying news given that ready-meals are almost as unhealthy as the meals prepared by many of the most popular chefs on the TV cookery shows (Howard et al., 2012; Meister, 2001; see also Food Standards Agency, 2003).

From restaurants to supermarkets, from stories in the press through to the sides of product packaging, serving suggestions are often showcased with the foods themselves presented in the most favourable and desirable (albeit unrealistic) manner possible: Many such food images tend to be much more appetizing than the actual products that they portray. In some cases, dishes are created solely with the visual aesthetic in mind (see www.theartofplating.com).[7] That said, the way in which a food is plated (i.e., presented visually) exerts an impact on people's flavour perception, and can modify people's subsequent food choices, not to mention their consumption behaviour (e.g., Deroy, Michel, Piqueras-Fiszman, & Spence, 2014; Michel, Velasco, Gatti, & Spence, 2014; Spence, Piqueras-Fiszman, Michel, & Deroy, 2014; Zellner, Loss, Zearfoss, & Remolina, 2014; see also Linné, Barkeling, Rössner, & Rooth, 2002).

Due to the exponential growth in the availability of digital interfaces and audiovisual media over the last century (think smartphones, tablets, and computer monitors), most people now have daily access to digital screens. As the years go by, the digital display (but also the in-built cameras) of these devices has been improving continuously in terms of resolution and the quality of the colour rendition, resulting in the pictures taken (and seen) having a greater aesthetic appeal too. Furthermore, more and more 'embellishing' technologies are also coming onto the market, from programs such as 'Photoshop' for photography amateurs and professionals, through to 'Instagram', where anyone can easily make their images more visually attractive. These new technologies are resulting in consumers' increasing exposure to digital food images, that is, divorced from the natural situations of consumption.[8] At the same time, the last few years have seen a dramatic rise in the dining public's obsession with taking images of the foods that they are about to eat, often sharing those images via their social media networks (e.g., see Abbar, Mejova, & Weber, 2015). The situation has reached the point now that some chefs are considering whether to limit, or even, on occasion, to ban their customers from taking photographs of the dishes when they emerge from the kitchen (e.g., see Alexander, 2014; Clay, 2014; Ensor, 2013; O'Neill, 2015). However, one restaurant consultant and publisher has recently suggested that the way food looks is perhaps more important than ever: "*I'm sure some restaurants are preparing food now that is going to look good on Instagram*" (Saner, 2015). Some chefs have even embraced this trend by providing diners with camera stands at their restaurant tables, even serving food on plates that spin 360°, thus allowing their customers to get the perfect shot every time (Elliott, 2015; Michel, Woods, Neuhäuser, Landgraf, & Spence, 2015). Books on the art of plating also urge the reader to make it look beautiful (e.g., Siple & Sax, 1982).

While it might seem that the influence of this 'digital grazing' is gaining traction across a wide cross-section of the public, there is a very real concern that this onslaught of appetizing food images may be having a deleterious impact on certain of our eating behaviours (e.g., see Ouwehand & Papies, 2010; Robinson & Matheson, 2014).[9] After all, it is already well-known that food advertising increases the consumers' wanting for food, hence increasing their consumption of whatever food happens to be within reach. This is true in both children and adults (Borzekowski & Robinson, 2001; Halford et al., 2008; Harris, Bargh, & Brownell, 2009). It would seem that 'visual hunger' may well activate those behaviours that are associated with food consumption in a manner that is relatively automatic.

Indeed, the pervasive visual exposure to food has already been shown to exert an essential role in terms of consumption behaviours: According to Wansink (2006), the food information derived from digital media is thought to influence over 70% of the food eaten by American households. At the same time, the dieting culture, together with lean ideals, contrast with what the media seems to want to indulge their viewers with (see Howard et al., 2012). Pope and her colleagues have recently suggested that this indulgence leading to *visual satiation* might just be an outlet for actual behaviours that are either obesogenic, or less acceptable in today's society, while the promotion of healthy eating has become commonplace. This paradoxical observation concerning media content attests to the 'vicarious gluttony' (see Adema, 2000), or 'vicarious consumption' (Pope et al., 2015)[10] that many people find themselves indulging in. Indeed, cooking shows, food advertisement, and social media feeds containing images of high-energy foods may well offer a substitute source of pleasure, while at the same time indirectly promoting overconsumption and gratification. As Passamonti and his colleagues (2009, p. 43) note, "*external food cues, such as the sight of appetizing food can evoke a desire to eat, even in the absence of hunger.*" The real problem here is that such indulgence, by modelling how much and what type of food we end up eating, might actually be detrimental to both our psychological and physiological well-being.

On the flip side, though, the hope amongst some researchers is that by gaining a better understanding of the neural underpinnings of our visually-elicited food behaviours, we may one day potentially be able to nudge consumers toward healthier eating (e.g., Toepel, Knebel, Hudry, le Coutre, & Murray, 2009).

3.1. On the (neuro-)physiological consequences of viewing food images

But are there really any indirect health-related consequences associated with the dramatic increase in our exposure to appealing images of foods (increasingly, via our smartphones and other mobile technologies)? What seems clear from a casual reading of the literature is that the exposure to images of desirable foods can trigger inhibitory cognitive processes such as self-restraint, that is, effortful processes associated with resisting the temptation that desirable foods constitute in order, one presumes, to maintain

[7] Indeed, there is a very real danger that by making food as visually appealing as possible, that is, by idealizing its visual appearance, we sometimes end up forgetting about, or downplaying, the importance of flavour, of foods that actually taste good, or that are ethically sourced.

[8] See *Marks & Spencer's* recent food campaign, for one particularly evocative example (http://www.huffingtonpost.co.uk/2014/09/02/marks-and-spencer-food-pudding-advert-this-is-not-just-any_n_5751628.html).

[9] Here, an analogy can be drawn with the on-going debate about the negative consequences on society of the non-edible variety of pornography (e.g., Lambert, Negash, Stillman, Olmstead, & Fincham, 2012; Maddox, Rhoades, & Markman, 2011; Malamuth & Check, 1985; Olmstead, Negash, Pasley, & Fincham, 2013). In fact, the link between sex and food, two primary reinforcers is a topic awaiting thorough academic study (e.g., see Crumpacker, 2006, for an engaging introduction). And according to Jamie Oliver, a highly influential chef and food entrepreneur, "food" is the second most searched for term on the Internet after, you guessed it, pornography (e.g., Cadwalladr, 2014; see also Carter, 2014).

[10] According to Pope et al. (2015), people, especially women, may use food television as an outlet for actual behaviours that are not so acceptable in today's society, cooking programs may offer pleasure vicariously. Pope et al. go on to say that: "*Because many cooking shows normalize overconsumption and gratification, it comes as no surprise that viewers' culinary habits are negatively influenced*" (Pope et al., 2015, p. 132).

a reasonably healthy weight (e.g., Fishbach, Friedman, & Kruglanski, 2003; Kroese, Evers, & De Ridder, 2009; Van den Bos & de Ridder, 2006; see also Uher, Treasure, Heining, Brammer, & Campbell, 2006).

Such inhibitory processes may be especially challenging for those who, for whatever reason, exhibit a tendency to overeat (e.g., Ouwehand & Papies, 2010; Passamonti et al., 2009).[11] Note here also that those individuals who suffer from binge-eating disorder and bulimia experience greater reward sensitivity, brain activation, and arousal, in response to viewing images of pleasant foods (e.g., Schienle, Schäfer, Hermann, & Vaitl, 2009). Obese individuals, by contrast, exhibit significantly less activation of the reward-related brain areas in response to food consumption than do healthy weight individuals. However, they show greater activation in the gustatory cortex and in somatosensory regions in response to anticipated food intake compared to healthy weight individuals. This pattern of results therefore suggests that those individuals who are overweight may anticipate more reward from food intake while at the same time experiencing less sensory pleasure as a result of eating (Stice, Spoor, Bohon, Veldhuizen, & Small, 2008).

Given the impact that visual images of food so obviously have on our eating behaviours, as outlined in the previous section, it should come as little surprise that the human brain preferentially directs its limited attentional resources toward the processing of high-fat foods (e.g., Toepel et al., 2009; see also Harrar, Toepel, Murray, & Spence, 2011). In one study, Toepel and his colleagues utilized a calibrated series of food images that had been developed to control for any low-level differences in terms of their visual characteristics (such as their luminance and spatial frequency distributions), but which varied in terms of their fat content. Using electrical neuroimaging of visual evoked potentials (VEPs), these researchers were able to demonstrate that the high-fat food images were processed differently, with this topographical difference in cortical processing showing-up pretty rapidly (that is, within about 165 ms of participants seeing the visual stimulus; see also Killgore et al., 2003).

Meanwhile, Harrar et al. (2011) used a subset of stimuli from the same database in order to demonstrate that high-fat food images also motivate human behaviour more effectively than do low-fat food images. In their study, participants had to make speeded target elevation discrimination responses to a series of visual targets presented to the left or right of central fixation. Shortly before the presentation of each target (at stimulus onset asynchronies of 100, 300, or 450 ms), a spatially-nonpredictive image (that participants were supposed to ignore) was flashed up on either the same or opposite side of the screen (see Fig. 1). The results of this study revealed that the participants responded more rapidly, and no less accurately to the targets following the presentation of high-fat food images than following the presentation of low-fat or no fat images.[12] A similar pattern of results was also obtained when the images were grouped in terms of whether high versus low carbohydrate foods were depicted. Harrar et al. (2011, p. 351) summarized their findings as follows: "*These results support the view that people rapidly process (i.e. within a few hundred milliseconds) the fat/carbohydrate/energy value or, perhaps more generally, the pleasantness of food. Potentially as a result of high fat/high carbohydrate food items being more pleasant and thus having a higher incentive value, it seems as though seeing these foods results in a response readiness, or an overall alerting effect, in the human brain.*"

The research that has been conducted over the last 5–10 years shows that attentional capture by food images tends to be more pronounced in those participants who are hungry than in those who are sated (Piech, Pastorino, & Zald, 2010; see also Siep et al., 2009). Attentional capture is also higher in response to food images that are judged to be more pleasant (di Pellegrino, Magarelli, & Mengarelli, 2011; see also Brignell, Griffiths, Bradley, & Mogg, 2009). The capture of attention by food stimuli is also modulated by an individual's body-mass index (BMI) (Nummenmaa, Hietanen, Calvo, & Hyönä, 2011; see also Yokum, Ng, & Stice, 2011). Now, given that covert shifts of a person's attention normally precede any overt shift of gaze, one might therefore consider whether such preferential attentional capture by certain types of food image might not also lead to a subtle biasing of consumer choice. However, while some published results support such a claim (namely, that we tend to choose the stimuli that first captures our attention), it is important to note that the jury would still appear to be out on this one (see Van der Laan, Hooge, de Ridder, Viergever, & Smeets, 2015, for recent debate).

In our everyday lives, of course, we rarely see images of food in isolation. That is, they are typically presented against a certain backdrop, be it the packaging of the food on which that image is presented, or the place setting when we are presented with a plate of food in a restaurant setting. Zhang and Seo (2015) recently found that the amount of attention that people devote to images of food depends on background saliency (i.e., it changes as a function of both table setting and decoration) and culture.[13] In summary, the research that has been reported to date clearly demonstrates that the consumer's brain tends to direct its limited attentional resources (first covertly, then overtly) toward the energetic food sources that currently happen to be in the field of view.

3.2. Neural substrates underlying the processing of visual food cues

Food is one of the most effective stimuli in terms of modulating brain activity in hungry participants (see Fig. 2), with the sight and smell of appetizing food leading to a striking 24% increase in whole brain metabolism in one representative PET study (see Wang et al., 2004; see also LaBar et al., 2001).[14] This is no mean feat when it is remembered that the brain is the body's most energy-hungry organ, accounting for something like 25% of blood flow/available consumed energy (Aiello & Wheeler, 1995; Wenk, 2015). Remarkably, pretty significant changes in neural activity are also elicited if a participant happens to see nothing more than the static visual image of a desirable foodstuff on a monitor while lying passively in a brain scanner.

Van der Laan et al. (2011) conducted a meta-analysis of 17 different neuroimaging studies (involving almost 300 participants) in which the neural activation elicited by the visual presentation of food images had been assessed. While nearly 200 separate foci of activation were highlighted across this diverse set of studies, the results of the meta-analysis revealed a small number of key brain regions that were activated in response to food pictures (across a number of the studies). So, for example, the bilateral posterior fusiform gyrus, the left lateral orbitofrontal cortex (OFC), and the left middle insula all exhibited increased neural activity following the presentation of food images in several of the studies. Separately, the hunger state of the participants modulated the brain's

[11] As Passamonti et al. (2009, p. 43) put it: "*Eating is not only triggered by hunger but also by the sight of foods. Viewing appetizing foods alone can induce food craving and eating, although there is considerable variation in this "external food sensitivity" (EFS). Because increased EFS is associated with overeating, identifying its neural correlates is important for understanding the current epidemic of obesity*."

[12] Interestingly, though, the magnitude of the stimulus-driven, or exogenous, spatial cuing effect was unaffected by the type of image that was shown visually, thus suggesting that the presentation of the food images had a more general effect on participants' motivation/arousal levels rather than specifically enhancing spatial attentional capture.

[13] The visual attention of the Chinese participants in Zhang and Seo's (2015) study was directed to the food in the images a little later in time than was the case for the North American participants whose behaviour was assessed.

[14] As Gordon Shepherd (2014) put it recently in a conference presentation: "*Flavor engages more of the brain than any other activity.*"

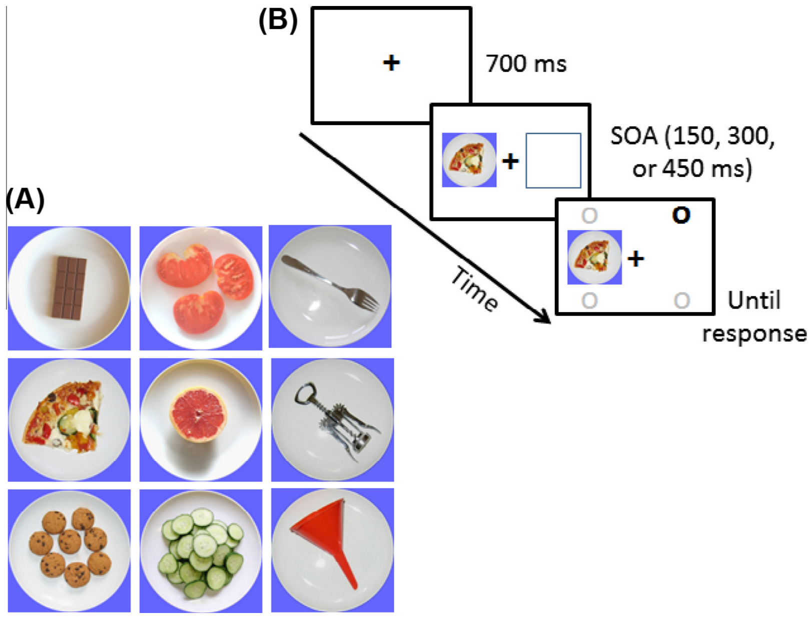

Fig. 1. (A) A subset of the three types of image used in Harrar et al.'s (2011) study of attention capture by high-fat (or high-carbohydrate) food images: high-fat food (left column), low-fat food (middle column), and non-food items (right column). (B) Methods. The first frame shows the fixation cross, which was shown for 700 ms. The second frame shows the visual cue (a slice of pizza) appearing to the left of the fixation cross—a dashed rectangle shows the other possible location where the visual cue could occur. The third frame shows a visual target (not drawn to scale) presented in the top right (the other three possible locations for the visual target are depicted by faint circles). The condition shown in the figure is a non-cued trial with a high-fat food image. [Figure adapted from Harrar et al. (2011).]

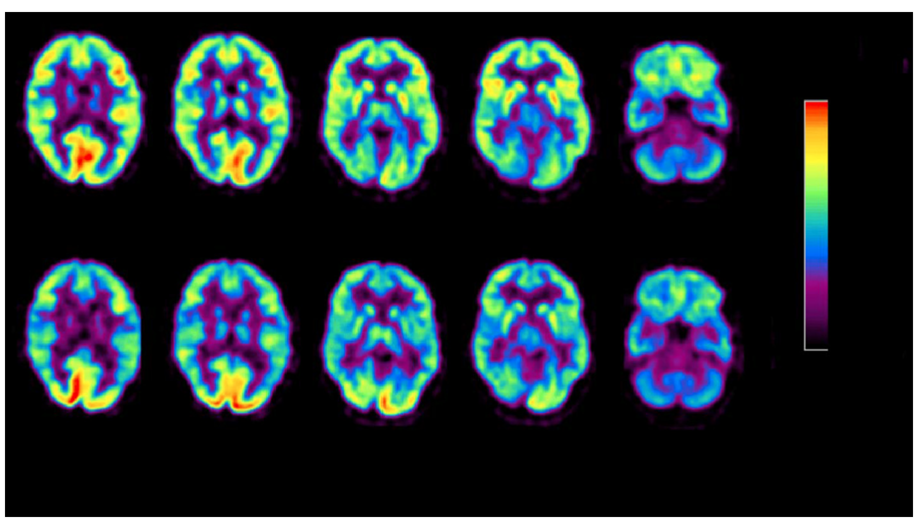

Fig. 2. PET images from one of the hungry participants who took part in Wang et al.'s (2004) study of brain activity in response to the presentation of, and talking about, appetizing foods. In the food presentation condition, the participants (whose last meal had been between 17 and 19 h earlier), had to describe their favourite foods and how they liked to eat them. At the same time, they were presented with foods that they had reported as being amongst their favourite, the food was warmed to ensure the delivery of appetizing food aromas too. Furthermore, cotton swabs that had been impregnated with one of the participant's favourite foods were placed on their tongues so that they could taste it as well. A 24% increase in whole brain metabolism was documented on being shown appetizing images of food while lying in a brain scanner. (Red represents the highest metabolic activity and dark violet the lowest.) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

response to food pictures in the right amygdala and left lateral OFC. Finally, the response in the hypothalamus/ventral striatum was modulated by the expected energy content of the food.[15]

More recently, Pursey et al. (2014) conducted a meta-analysis of 60 different neuroimaging studies (involving a total of 1565 participants) that had assessed the neural response to visual food cues as a function of the weight of their participants. In this case, the results revealed that obese individuals exhibited a greater increase in neural activation in response to food as compared to non-food images, especially for high-calorie foods, in those brain regions that are associated with reward processing (e.g., the insula and OFC), reinforcement and adaptive learning (the amygdala, putamen, and OFC), emotional processing (the insula, amygdala, and cingulate gyrus), recollective and working memory (the amygdala, hippocampus, thalamus, posterior cingulate cortex, and caudate), executive functioning (the prefrontal cortex (PFC), caudate, and cingulate gyrus), decision making (the OFC, PFC, and thalamus), visual processing (the thalamus and fusiform gyrus), and motor learning and coordination, such as hand-to-mouth movements and swallowing (the insula, putamen, thalamus, and caudate).

[15] Though interestingly, it turns out that there can actually be quite a mismatch between the expected satiety of foods (as assessed from their visual appearance) and their actual energy content (e.g., Brunstrom, Shakeshaft, & Scott-Samuel, 2008; see also Davies, 2015; Jimenez et al., 2015).

Those individuals who were obese were also shown to be more responsive to food cues when in a satiated state than were the healthy weight individuals. In the fasting state, obese individuals demonstrated increased neural activation in those areas that are known to be associated with the anticipation of reward. By contrast, healthy weight controls exhibited greater activation in those neural areas that are associated more closely with cognitive control. Results such as these therefore suggest that the weight and hunger state of the consumer/participant in a neuroimaging study exerts a significant influence on the reward responsiveness of their brains to pictures of food. The healthiness and the perceived tastiness of food images also influence the brain's response, especially in those individuals with a higher BMI.

Petit et al. (2014) reported that when participants viewed pictures of healthy foods while thinking about the pleasure that they would get, were they to eat them, greater activation was seen in individuals with higher BMI than in lean individuals in those brain areas that are associated with cognitive control (inferior frontal gyrus) and the anticipation of reward (insula, orbitofrontal cortex). On the other hand, when those individuals with a higher BMI viewed the same images while thinking about the possible health benefits, less activity was observed in these same brain areas. These results suggest that individuals with a higher BMI tend to dismiss the health benefits, and that promoting the tastiness of healthy food improves their self-regulation capabilities.

Before closing this section, though, it is perhaps worth pausing for a moment to consider just how far removed from the real-world of multisensory food consumption is the experience of those participants who agree to take part in one of these neuroimaging studies (see Spence & Piqueras-Fiszman, 2014).[16] Notice how the participants typically have to stare passively at carefully-controlled, but not necessarily all that appealing, images of food (i.e., unisensory stimulation) with no real expectation that they will have the opportunity to eat any of the foods that they see (in this way, perhaps mirroring the situation for all of those consumers watching all those food shows on TV). Given such constraints, it might well be anticipated that the changes in brain activation that are likely to be associated with the presence of real food prior to an actual consumption experience (with all the multisensory stimulation that normally entails), will be much higher than has typically been reported in the neuroimaging studies that have been summarized in this section (cf. Spence, 2011).

3.3. Influence of food images of psychology/physiology

Not only do food images result in profound changes in attention as well as in neural activity across a network of brain areas (see above), they can also lead to increased salivation (at least if the food images are combined with other food-related sensory cues; see Spence, 2011, for a review), not to mention a number of other physiological changes. Changes in the cephalic phase release of insulin have been reported following the presentation of food images, as well as changes in heart rate in anticipation of the food that is expected to come (e.g., Drobes et al., 2001; Wallner-Liebmann et al., 2010). Interestingly, here, the large body of older research on the exogenous factors that elicit a salivatory response are illustrative in showing how much more of a (salivatory) response one is likely to see the more sensory cues one incorporates in the stimulation that is presented to the participant, and the closer to a real food consumption episode that one can get.

Food pictures can also modify the process of hedonic taste evaluation. By means of electro-encephalography (EEG), Ohla, Toepel, Le Coutre, and Hudry (2012) showed that high (vs. low) calorie food images enhance the hedonic evaluation of a subsequently-presented hedonically neutral electric taste produced by a small current that was applied to the tongue. At the behavioural level, the participants rated the electrical taste as significantly more pleasant after viewing high-calorie food images than after viewing the low-calorie food images. At the cerebral level, high-calorie food images induced an early modulation of taste-evoked neural activity in the insula/frontal operculum (FOP) within 100 ms after taste onset. Such a pattern of results clearly suggests that visual information concerning the energy-content of a food modulates taste representations during the early level of stimulus encoding in the primary taste areas. The later differences of activation that were seen in the OFC (at a latency of 180 ms), and which were positively correlated with the hedonic evaluation of the taste, were followed by subsequent modulations of activation in the insula/FOP at a latency of around 360 ms. This late activation suggests an interoceptive hedonic re-evaluation of the taste based on the perceived energy-content of the food images.

In a sense, one can question here whether the appearance of digitally enhanced food-related sensory experiences, such as olfactory apps (e.g., see http://www.bbc.co.uk/news/technology-26526916), virtual taste (Ranasinghe et al., 2011), cooking simulation computer games (e.g. Cooking Mama: http://en.wikipedia.org/wiki/Cooking_Mama), and virtual reality food experiences (http://www.projectnourished.com/), no matter how realistic they might be, might actually be having the opposite effect to the one that they market themselves on. There is even talk of enhanced 3D VR food blogs (see Perception Fixe, by Matheus De Paula Santos of Myo Studios). According to Swerdloff (2015): "*Myo Studios is banking on the notion that providing an enhanced visual experience through virtual reality will markedly up its food blog's ante. Users will be able to "sit down in front of a steak from some restaurant, even though there's no reservation for three months." ... DePaulaSantos told me, "One of my hopes is to not just take photographs of food, but also be able to animate it. If you see a sizzling steak in front of you, that's just one way of stimulating more senses.*"

3.4. Interim summary

What we have seen so far, then, is that the human brain is the body's most demanding organ in terms of energy-consumption, that one of the primary functions of brain function is to find nutritious sources of food, that high-energy food images preferentially receive processing resources, and that the unisensory visual presentation of food images can lead to profound changes in cerebral activity, especially in hungry individuals. It is at this point that we need to consider the changing face of the food landscape for humans during the twentieth century: From hunter-gatherers evolving by means of natural selection, we have increasingly grown to be super-consumers, the primary predator of the planet's limited natural resources. Our search for food no longer takes place out in the wild, but involves industrial food production at one end, and the shoppers' navigation of the supermarket aisle (and increasingly online) at the other (Sobal & Wansink, 2007).

It has been argued by many that the oversupply of food has led to the growing obesity crisis faced by many of the countries in the developed world (e.g., Caballero, 2007; Critsen, 2003; Moss, 2013; World Health Organization, 1998). Blame here is often laid at the doors of the global food companies (Moss, 2013), pumping out addictive foods, designed to hit 'the bliss point' in terms of sugar, salt, fat, etc. (Moskowitz & Gofman, 2007; Wrangham, 2010, p. 195). However, our aim in the section that follows is rather to take a closer look at the potential role of vision, and specifically the growing exposure to appetizing high-fat images of food in exacerbating our overconsumption of food.

[16] It can, of course, be difficult to capture the realistic situation of food consumption while one's participant is clamped still in the brain scanner; see Spence & Piqueras-Fiszman, 2014).

4. Eating with our eyes: Visual hunger in the digital age

As we saw earlier, 'visual hunger' can be defined as the natural desire, or urge, to see food images and the subsequent array of neural, physiological, and behavioural responses that result from an individual's exposure to food images – typically implying unisensory (visual) stimulation in the absence of any actual food. The existence of this phenomenon could be put down as an early Pleistocene adaptation to the comfort of seeing food, meaning to early humans having enough energy to survive for a few more days. The rise of painting and the visual arts made it possible to depict food without any actually being present. In recent times, the appearance of print, and thereafter digital screens – whose presence in the daily lives of modern humans is seeing an exponential growth – has rendered the presence of virtual food ubiquitous. As advanced in this article, the regular exposure to virtual foods might well be exacerbating our physiological hunger more often than needed, due to the array of neural, physiological, and behavioural responses linked to seeing food. Given the fact that a growing proportion of the world's population lives in obesogenic environments, this doesn't seem to be helping in solving certain costly food-related diseases that are of concern to certain influential organizations and public policy makers, not to mention the environmental consequences related to the growing production of such foods. We believe that discussing and understanding the importance of the unimodal visual presentation of food in today's environment is important in terms of orienting populations towards more appropriate food behaviours and choices, a subject of great importance given the fact that some of the biggest challenges facing humankind are related to food consumption and food systems – health, excessive meat-consumption, the use of natural resources, water management, land use – to name just a few.

In society at large, there is a growing awareness of just how much people like to take pictures of the food that they have ordered in restaurants, and chefs wanting to design food in most pleasing manner. Increasingly, it would appear that people are spending more time looking at virtual images of appetizing foods, and paying less attention to the actual foods being consumed (see Fig. 3). Worse still, many of us eat while mindlessly watching screens (TV, or smartphone), failing to focus our attention on the flavour experience which might the very source of lower satiety, and higher-calorie food intake: The pleasure of seeing virtual food (the hunger for images, or 'digital grazing') while eating has in some sense superseded the pleasure of seeing the real thing. And while some might be tempted to see this as the fault of industry/marketers, it is important to remember, given the growing popularity of consumers taking pictures of food,[17] that the problem here would appear to be, at least partly, self-inflicted.[18]

4.1. From real cooking to virtual feeding

Here, one might also want to consider the consequences of our increasing reliance on processed foods, driven both by its low price and its convenience (e.g., Moss, 2013). According to Eric Schlosser (2001, p. 121), in his best-selling book *Fast Food Nation*: "*about 90% of the money spent by North Americans on food is used to buy processed food*". Note that beside the negative health consequences that are typically associated with a diet that involves the consumption of large quantities of such foods (see Moss, 2013), one little-considered consequence is that when the food comes pre-prepared, all of the sensory (including visual) cues that are normally associated with food preparation are essentially eliminated. Might it be, then, that the current obsession with viewing others cooking on the television, and reading endless beautifully-illustrated (gastroporn) cookbooks (Allen, 2012, p. 74; Baumann, 1996, p. 121) can be framed as an implicit coping strategy designed to make up for the loss of all the cooking-related sensations (a kind of virtual comfort if you will; Prince, 2014)? As Allen (2012, p. 74) notes, there certainly needs to be some account of why there are now so many more cookbooks out there than anyone could ever manage to cook from over a lifetime. And what impact, one has to ask, is submitting to our hunger for visual images of food having on our patterns of consumption (Boyland et al., 2011)?

4.2. Using visual images to encourage healthy eating

In closing, it is worth noting that while the increased visual exposure to food images has generally been framed as having a negative impact on people's food consumption, this need not always be the case if visual stimulation is curated properly, and used in a timely manner (see also Boulos et al., 2012). There are, in fact, certain situations in which the increased visual exposure to food images can actually exert a beneficial effect over people's food behaviours. So, for example, young children's liking for vegetables can be increased simply by exposing them to pictures of those vegetables (e.g., in books; Houston-Price, Burton, et al., 2009; Houston-Price, Butler, & Shiba, 2009). Intriguingly, visual exposure to food images can also induce satiety: Similar to the gradual reduction of hunger that is seen during actual consumption (Redden & Haws, 2013), even just the simulation of consumption can reduce hunger (Morewedge, Huh, & Vosgerau, 2010). Morewedge et al. demonstrated that the mere act of imagining eating a large number of M&M's (vs. a small number) significantly reduced people's subsequent consumption of these candies. Perhaps even more surprising, though, are recent findings showing that simply viewing 60 (vs. 20) food pictures associated with a specific taste experience (e.g. salty) decreased people's enjoyment of similar taste experiences during consumption (Larson, Redden, & Elder, 2014).

Another, more indirect, benefit of exposure to food images is linked to the work of the growing number of researchers who are presenting visual food images (e.g., over the internet) in an experimental setting – that is, to assess people's preferences for one configuration of the elements versus another (e.g., Michel et al., 2015; Reisfelt, Gabrielsen, Aaslyng, Bjerre, & Møller, 2009; Youssef, Juravle, Youssef, Woods, & Spence, 2015). The results of such research will hopefully increasingly be used to help food providers optimize the visual presentation of the foods that they serve, and could one day even feed into public health policies and cleverly designed virtual food content. One could certainly see how figuring out how to make healthy food more attractive visually might one day potentially play a role in terms of encouraging people to eat more healthily (see Michel et al., 2014).[19]

[17] This may all come down to the fact that, it is simply much easier to enhance (or hack) the aesthetic pleasantness of food on-screen, thanks to the increasing high-definition of portable cameras and the pre-made filters (Instagram), and, at a professional level, the technology available to beautify the visual renderings of the food. Indeed, one increasingly also sees explicit recommendations to the public with titles such as: "*How to turn your dull food images into Instagram food porn*" (e.g., see Victor, 2015b)

[18] Interestingly, the fact that visual stimulation is so complex in nature might be one of the reasons why our attention is so easily captured by screens, even while eating. The problem might be, then, that if our attention is directed to visual stimuli while eating, this may well result in reduced satiety and thus lead to a higher-energy intake (e.g., Boulos et al., 2012; Braude & Stevenson, 2014; Gore, Foster, DiLillo, Kirk, & West, 2003; Robinson & Matheson, 2014).

[19] Note how such research is firmly based on the belief that the expectation about food that have been set visually will anchor the subsequent experience should we actually get to taste whatever we are looking at (see Piqueras-Fizman & Spence, 2015, for a review).

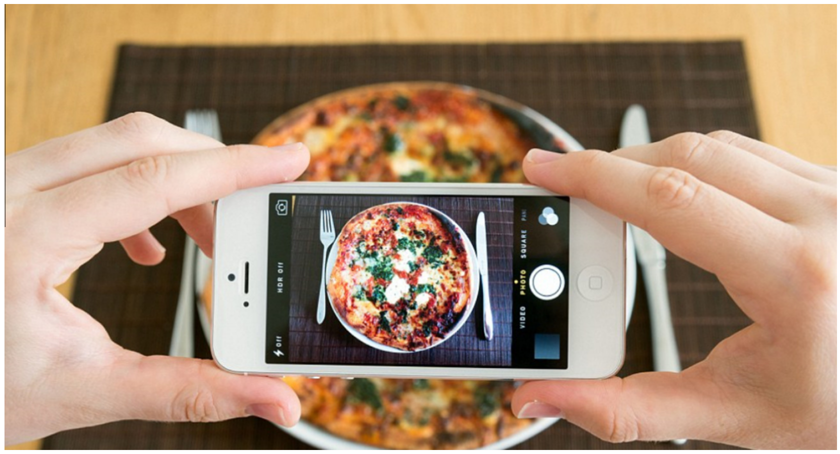

Fig. 3. What is the impact, and what is the cause, of our growing food porn addiction (Victor, 2015b)?

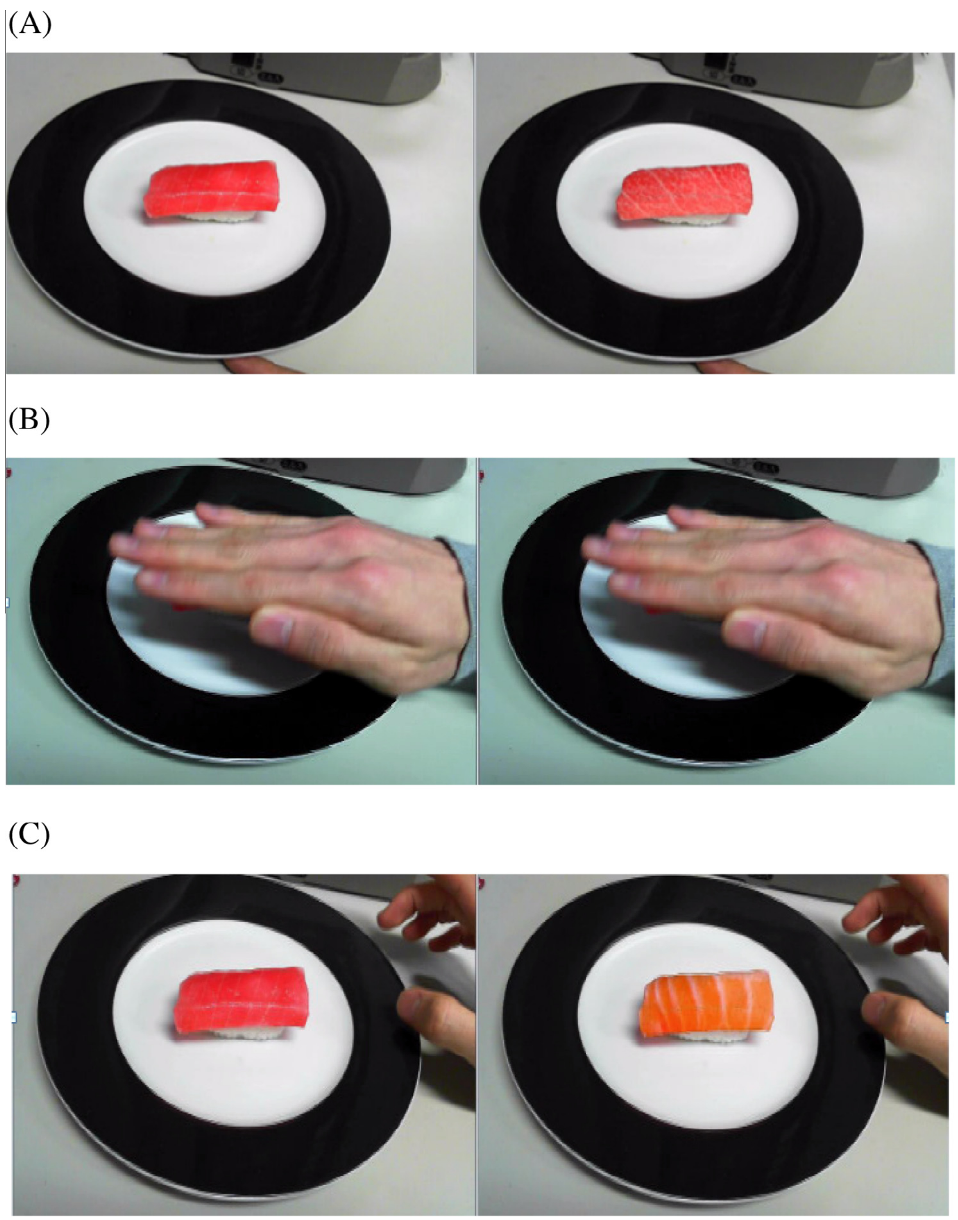

Fig. 4. Still images from AR sushi demo. (A) and (C) The original sushi (tuna) on the left and the augmented versions (fatty tuna and salmon, respectively) on the right. (B) Hand action used as a trigger to change the visual texture. See http://www.okajima-lab.ynu.ac.jp/demos.html for a video. [Video courtesy of Prof. Katsunori Okajima, Dept. Environment & Information Sciences, Yokohama National University, Japan.]

And, looking a little further into the future, it will be interesting to see how the various new augmented and virtual reality (AR and VR, respectively) technologies that are currently starting to appear at the technology conferences, and occasionally, in the marketplace, will allow the diners of the future to eat one food while simultaneously viewing another (e.g., Choi, Foth, & Hearn, 2014; Narumi, Ban, Kajinami, Tanikawa, & Hirose, 2012; Okajima & Spence, 2011; Okajima, Ueda, & Spence, 2013; Schöning, Rogers, & Krüger, 2012; Swerdloff, 2015; Victor, 2015a). The AR system utilized by Okajima et al. can change the visual appearance of any food, including drinks in real time. Importantly, this can be done without the need for any marker to be placed on the food itself. Under these conditions, changing the visual appearance of the food was shown to dramatically modify the taste, as well as the perceived texture, of foods, such as cake and sushi (see Fig. 4). Here, one could imagine a consumer viewing what looks like a highly-desirable, but unhealthy, food which actually eating a healthy alternative.

5. Conclusions

One of the primary functions, or challenges, faced by the brain is to find nutritious foods and to avoid ingesting those substances that may be poisonous or otherwise harmful. While the senses of taste (gustation), smell (olfaction), and texture (touch or oral-somatosensation) provide the ultimate arbiters of a food's palatability, it is the sense of vision that provides a far more effective means of foraging, predicting which foods are likely going to be safe and nutritious to consume, and generating those expectations that will constrain the consumption experience. Contemporary neuroscience demonstrates just what a powerful cue the sight of appealing food can be for the brain, especially the brain of a hungry person.

Given the current obesity crisis (Flegal, Carroll, Ogden, & Curtin, 2010), it would seem advisable to pay particular attention to any environmental factor that may influence our relation to food, and potentially sensitize the brain to food stimuli (see Castellanos et al., 2009; Marteau et al., 2012; Stoeckel et al., 2008). According to the body of research that has been outlined here, one candidate factor that most certainly deserves a closer look is the increasing prevalence of high fat food images that surround us in both the real and virtual food landscape. Crucially, the question that has yet to receive a satisfactory answer is just what the impact of all those appealing food images is having on the consumption behaviour of those in the Western world who are both flooded with opportunities to eat, and at the same time bombarded with gastroporn (cf. Berthoud, 2011). In the years to come, answering such questions will likely become increasingly important for those of us who are 'lucky' enough to be surrounded by an abundance of food, both real and virtual.

Given the essential role that food plays in helping us to live long and healthy lives, one of the key challenges outlined here concerns the extent to which our food-seeking sensory systems/biology, which evolved in pre-technological and food-scarce environments, are capable of adapting to a rapidly-changing (sometimes abundant) food landscape, in which technology plays a crucial role in informing our (conscious and automatic) decisions.

Competing interests

The authors declare no competing interests.

Author's contributions

CS, CM, OP, and AC contributed to the writing of this paper. All of the authors read and approved the final version of the manuscript.

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