REVIEW

OPEN

The dynamic nature of food reward processing in the brain

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Purpose of review
The dominant view in the literature is that increased neural reactivity to high-caloric palatable foods in the mesocorticolimbic system is a stable-specific characteristic of obese people. In this review, we argue that this viewpoint may not be justified, and we propose that the neural response to food stimuli is dynamic, and in synchrony with the current motivational and cognitive state of an individual. We will further motivate why a clear mental task in the scanner is a necessity for drawing conclusions from neural activity, and why multivariate approaches to functional MRI (fMRI) data-analysis may carry the field forward.

Recent findings
From the reviewed literature we draw the conclusions that: neural food-cue reactivity depends strongly on cognitive factors such as the use of cognitive regulation strategies, task demands, and focus of attention; neural activity in the mesocorticolimbic system is not proportionate to the hedonic value of presented food stimuli; and multivariate approaches to fMRI data-analysis have shown that hedonic value can be decoded from multivoxel patterns of neural activity.

Summary
Future research should take the dynamic nature of food-reward processing into account and take advantage from state-of-the-art multivariate approaches to fMRI data-analysis.

Keywords
functional MRI, multivoxel pattern analysis, obesity, reward value food

INTRODUCTION

The problem of overweight and obesity has reached pandemic proportions in the Western world and is associated with severe negative health outcomes [1]. A dominant view in the literature assumes that, in overweight people, the perception of high-caloric palatable food automatically triggers their neural reward system, leading to increased food consumption [2▪]. More specifically, it is predicted that the neural response in key reward-related areas in the brain (striatum, midbrain, orbitofrontal cortex, medial prefrontal cortex, amygdala, anterior insula, frontal operculum, hippocampus, parahippocampal gyrus) is enhanced upon the perception of food cues (e.g. images of food), and reduced upon the actual consumption of food, in overweight people.

However, these predictions have not received consistent empirical support. A meta-analysis on the neural correlates of visual perception of food stimuli in healthy-weight participants concluded that the convergence over studies was moderate, as maximally 41% of the included studies contributed to the significant clusters of activation [3]. Ziauddeen *et al.* reviewed functional neuroimaging studies comparing obese and healthy-weight people's neural responses to food stimuli, and drew the provoking conclusion that 'the pattern emerging from studies comparing obese individuals and binge-eaters with controls is most remarkable for its variability and inconsistency.' [[4]; p. 283].

In this study, we will review recent evidence supporting the dynamic nature of food reward processing in the brain. We will argue that it may not be justified to view the neural response to food stimuli as a fixed characteristic of overweight versus

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KEY POINTS

- The level of neural activity in the mesocorticolimbic system of the brain is not proportionate to the hedonic value of visually presented food stimuli.
- The mesocorticolimbic system may be better considered a motivational saliency network instead of a reward-network.
- Neural food-cue reactivity should not be considered a static characteristic of overweight versus healthy-weight people, but as in synchrony with people's current cognitive and motivational state (i.e. the use of cognitive regulation strategies, task demands, and focus of attention).
- Uncertainty about the mental process in which the participant is engaged in during scanning complicates the interpretation of the results of these studies.
- Multivariate approaches to fMRI data analyses have shown that hedonic value can be decoded from multivoxel patterns of neural activity.

healthy-weight people. Instead, the neural response to food stimuli is proposed to be in synchrony with the current motivational and cognitive state of an individual. In addition to reviewing evidence for this idea, we will reflect on what actually can be concluded from activity in reward-related brain regions, and how the field may benefit from multi-voxel pattern analysis (MVPA).

NEUROIMAGING OF FOOD-CUE REACTIVITY AND CONTROL

The basic assumption in much neuroimaging work is that visual food stimuli automatically trigger neural food-cue reactivity [5▪]. Research aims to test whether this neural food-cue reactivity is enhanced in overweight and obese people, thereby assuming that the elicited neural food-cue reactivity is a relatively fixed characteristic of people. Additionally, some neuroimaging work aims to test if the regulatory response to food stimuli is diminished in overweight as compared to healthy-weight people. This perspective is in line with dual-process models, which include a so-called 'hot' system (automatic positive response to food stimuli) and 'cold' system (a slower regulatory, inhibitory response) [5▪]. Recently, it has been proposed that it is the balance between the neural reward and control response that determines self-regulatory success [6▪].

One reason for the large inconsistency in the obesity neuroimaging work could be that the assumption of consistent neural responding to food stimuli is not warranted. The lack of consistency may stem from the double-sided nature of high-caloric food perception: High-caloric foods often have a high hedonic value and at the same time these foods have a low health value because their overconsumption contributes to weight gain. Instead of assuming that hedonic value always takes precedence, it may be more justifiable that hedonic value and health value both can determine the neural response to food stimuli, depending on people's motivational, emotional, cognitive or psychological state, or on the situation or context [7▪▪,8▪].

Most previous work that studied differences in neural food-cue reactivity between overweight and healthy-weight people used passive viewing paradigms, in which pictures of food were presented without a clear task for the participant. It may very well be that participants in these studies alternated (frequently) between focusing on health-value (e.g. viewing the presented chocolate as a load of calories) and hedonic value (e.g. viewing the presented chocolate as a treat). Unbeknownst to the researcher, these alternations may occur within a participant, and may vary between participants and between studies, affecting neural responses, and thereby leading to an inconsistent literature on this topic. What is the evidence so far that the neural responses to food stimuli are dynamic?

COGNITIVE MODULATION OF NEURAL RESPONSES TO FOOD STIMULI

Earlier work for example showed that overweight people's neural response in reward-related regions of the brain was only larger than in healthy-weight people when the task in the scanner was focused on taste-evaluation, but not when participants made a free choice of food stimuli [9]. Building on this earlier work [for partial review, see [10▪]], several recent functional MRI (fMRI) studies provide further evidence for the cognitive modulation of the neural response to food stimuli.

Two recent studies assessed the neural correlates of cognitive regulation strategies: thought suppression and reappraisal. Miedl *et al.* presented chocolate and neutral pictures, and instructed high versus low trait chocolate cravers to either think freely or to suppress thoughts about chocolate or a neutral object after the picture had disappeared. Collapsed across the think freely and suppress conditions, in chocolate blocks, high trait chocolate cravers thought about chocolate more often than did low trait chocolate cravers, and this was paralleled by higher neural activity in the striatum in high trait chocolate cravers. Though high trait cravers were specifically successful at chocolate thought suppression in the suppress condition, this was not paralleled by specific neural activity [11■]. Note that these researchers, unlike with passive viewing paradigms, had some behavioral evidence for the ongoing mental process: self-reported frequency of chocolate thoughts assessed after each block during scanning.

As was thought suppression [11■], reappraisal – thinking about negative health consequences – was effective in reducing self-reported craving. Moreover, this strategy was associated with increased neural activity in control-related regions of the brain (dorsolateral, ventrolateral, and dorsomedial prefrontal cortex) and reduced activity in a reward-related region of the brain (ventromedial prefrontal cortex) [12].

Another recent study did not address cognitive regulation, but instead focused on task demands [13■]. Neural reactivity to visual food versus nonfood stimuli was measured, with one group of participants focusing on color and the other on edibility. For the color focus, neural activity was specifically enhanced in the visual cortex and insula (gustatory cortex), whereas for the edibility focus, neural activity was specifically enhanced in the anterior cingulate cortex (ACC). Neural activity in the orbitofrontal cortex did not vary significantly with task focus. These differences in neural activity between task demands likely reflect a focus on low-level features (color) versus high-level features (edibility).

A healthy diet is not only determined by the type of food but also by portion size [14]. A recent study tested the effect of attentional focus on portion size decisions and its neural correlates [15]. It was found that when participants' attention was focused on eating for health or pleasure, the selected portion size was smaller, whereas the selected portion size was bigger when planning to be full until dinner. These behavioral results were paralleled by increased activity in the orbitofrontal cortex (pleasure attention focus), the left prefrontal cortex (health attention focus), and the left insula (fullness attention focus; trend), as observed in region of interest analyses.

Finally, one recent study tested the effect of attentional focus (pleasantness, calories, or intensity) while actually tasting liquid food stimuli (water, fruit juice, and tomato juice) [16]. When tasting – pooled over all three liquids – was contrasted with a low-level visual baseline (fixation cross), a large network of regions implicated in taste and reward processing was active, which is not surprising because of the large difference between the act of tasting liquids versus viewing a fixation cross. Still, effects of attention focus were observed, in that neural activity was enhanced in several taste-related and reward-related regions of the brain for the pleasantness as compared to intensity attention focus, and enhanced in the orbitofrontal cortex for the intensity as compared to the health attention focus.

Taken together, results from these recent as well as older neuroimaging studies are very much in line with the idea that neural activity associated with the perception of food stimuli is not static. Instead, it depends on cognitive factors such as the use of cognitive regulation strategies, task demands, and focus of attention.

FUNCTIONAL MRI NEEDS BEHAVIOR

Studies that provide evidence for the dynamic nature of neural representations of food also underline the importance of a clear mental task for participants in fMRI studies. Uncertainty about the mental process in which the participant is engaged in complicates the interpretation of the results of these studies.

In most studies on food-reward processing in obesity in which passive-viewing paradigms are used, the argument takes the following form: It is found that the neural response to food stimuli is larger in obese than healthy-weight people in certain areas of the brain that have previously been associated with reward processing. This is then taken as evidence that therefore the presented foods are more rewarding for obese than healthy-weight people. However, this form of reasoning is not particularly strong and fully depends on reverse inference: 'to infer the likelihood of a particular mental process M from a pattern of brain activity A (P(M|A))' [[17], p. 693]. As Poldrack explains, the probability that a certain mental process is engaged given certain neural activity (P(M|A)) depends both on the base rate of the observed neural activity and on the probability that the mental process is indeed engaged (P(M)). P(M|A) becomes less likely if the base rate of A is high, that is, if activity in a certain brain area is related to many different mental processes, and/or if P(M) is low [17]. Note that P(M) is unknown in a passive viewing paradigm because the researcher does not know how the participants process the presented food stimuli, and the mental process may fluctuate over the course of the scanning session.

Based on an online database (http://www.neurosynth.org), Poldrack [17] concludes that, among many others brain regions, certain frontal regions (ACC, anterior insula) have high base rates, and these areas are often included in the reward/control-system of the brain. These high base rates, combined with uncertainty about the mental process the participant is engaged in with passive viewing paradigms, shed doubt on the strength of reverse inference here, and limits the conclusions that can be drawn from these studies.

Recent findings from our laboratory further strengthen this argument (Franssen S, Jansen A, van den Hurk J, *et al*. Power of mind: attentional focus rather than food palatability dominates neural responding to visual food stimuli, submitted for publication). In this study, we tried to control the mental process of our participants as much as possible. We either had overweight participants perform a fast-paced hedonic 1-back task (i.e. indicate if the presented food is more or less palatable than the previous one; hedonic attentional focus) or a fast-paced neutral 1-back task (i.e. indicate if the presented food contains more or fewer colors than the previous one; neutral attentional focus). In the task, we presented individually tailored highly palatable and highly unpalatable high-caloric food stimuli. Strikingly, the level of neural activity in the mesocorticolimbic system was not significantly different for highly palatable versus highly unpalatable food stimuli, not even when participants focused on the taste. Instead, the neural response in several brain regions included in this system was larger with the hedonic attentional focus than with the neutral attentional focus, independent of the palatability of the presented food stimuli. So, neural activity was different between attentional foci while the exact same visual food stimuli were presented. These suggest that the level of neural activity in these regions may reflect motivational salience instead of being proportionate to the hedonic value of presented stimuli. Note that these findings align well with recent research that showed that the medial and lateral orbitofrontal cortex were largely equally responsive to stimuli representing positive and negative affect [18].

Future research addressing obese – healthy-weight differences in neural responding to high-caloric food stimuli may be well advised to take this into account, and make sure to use a paradigm that provides tight control over the mental process the participant is engaged in while being scanned. This allows for a better interpretation of neural findings, and may contribute to more consistency in this literature.

DECODING MENTAL STATES

Most neuroimaging work on neural correlates of food reward processing used a mass-univariate approach to fMRI data-analysis. Although these univariate analyses of fMRI data are only informative regarding the involvement of certain brain regions in certain tasks, MVPA of fMRI data decodes representational content in the brain [19▪]. So, two types of food can involve a brain region to a similar degree (result from conventional mass-univariate analyses), but can elicit very different multivoxel patterns of activity within that brain region (result from MVPA of fMRI data).

Earlier work showed that although the level of activity elicited by positive and negative stimuli was the same in the orbitofrontal cortex, stimulus pleasantness could be decoded from multivoxel patterns of neural activity [18]. Fitting nicely with these earlier findings, Suzuki and colleagues showed that food value could be decoded from multivoxel patterns in the orbitofrontal cortex [20▪▪]. Also in line with these findings are results from a recent study from our laboratory (Franssen S, Jansen A, van den Hurk J, *et al*. Power of mind: attentional focus rather than food palatability dominates neural responding to visual food stimuli, submitted for publication). Here we showed that food palatability could be specifically decoded from multivoxel patterns of neural activity when participants' attention focus was hedonic during task performance. So, positive versus negative affect and palatable versus unpalatable food stimuli can be distinguished based on neural activity, but only when using a multivariate approach to data analysis.

CONCLUSION

The main conclusions of this study include: neural food-cue reactivity should not be considered a static characteristic of overweight versus healthy-weight people, but as in synchrony with people's current cognitive and motivational state; the level of activity in brain regions that are typically implicated in reward processing is not proportionate to the hedonic value of presented food stimuli, and therefore it may be more appropriate to view this brain circuit as a motivational saliency network; multivariate approaches to fMRI data analyses have been insightful and have shown that hedonic value can be decoded from multivoxel patterns of neural activity.

These conclusions fit well with the idea of value-based choice: 'selecting from a set of options based on their relative subjective value' [[7▪▪], p. 423]. So, the idea is that people integrate various aspects of an option (e.g., taste, healthfulness, costs, social circumstances, etc.) for determining choice, without automatically prioritizing hedonic aspects. In this model, attentional focus is given an important role, as it is considered a gatekeeper of which options are available for choice. This model is a departure from dual-systems models, which typically posit a 'hot' impulsive system and a 'cold' reflective control system. Note that several other authors have recently also casted doubt on the validity of dual-process models [21▪,22▪].

The recent finding that the level of neural activity in the mesocorticolimbic system of the brain is not proportionate to the hedonic value of visually presented food stimuli is not trivial (Franssen S, Jansen A, van den Hurk J, *et al*. Power of mind: attentional focus rather than food palatability dominates neural responding to visual food stimuli, submitted for publication). If studies report increased neural activity in response to high caloric food stimuli, this could be because of both positive and negative valence. Based on the observed neural activity, it cannot be concluded that the hedonic value of the presented stimuli is higher. So, this brain system could maybe better be viewed as a motivational saliency system. Finally, future research could profit from relatively recent multivariate approaches to data-analysis, and from brain stimulation and neurofeedback techniques, to further our understanding of neural mechanisms of obesity [19▪,23▪,24▪].

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Conflicts of interest

There are no conflicts of interest to be declared.

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