Focus on food

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Focus On Food:
Effects of Mindset, Hunger and Dietary Restraint on Attention Bias, Food Intake and Brain Responses to Food

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CHAPTER 1

General introduction

The conflicting food environment

Nowadays, food-related advertisements and foods are everywhere. When walking in a city, one will encounter numerous promotions of high-caloric foods, such as fast food. Similarly, television advertisement breaks contain various food commercials, mostly promoting high-caloric food. At the same time, messages about negative health effects of high-caloric food are also abundantly present, and society idealizes thin and fit bodies. So, today's food culture contains strongly conflicting messages. The way one reacts to food in this conflicted culture may depend on a person's current mindset. Mindset refers to the aspects that are central in one's mind when evaluating food (Bhanji & Beer, 2012). Mindset may fluctuate over time and these fluctuations could be influenced by subtle context cues (Werthmann, Jansen, & Roefs, 2016). Sometimes people might focus on hedonic aspects of food, like its taste or the satisfaction felt by food consumption, whereas at other times people might focus on health or weight-related aspects of food, such as the number of calories or nutritional value of food. For example, when eating out at a fancy restaurant, focus most likely will be on food enjoyment. In contrast, after a workout in the gym, focus will most likely be on health-related aspects of food. Eating styles, like the chronic intention to diet, might influence which mindset people most frequently endorse. More specifically, when dieting, high-caloric food might appear threatening and the negative health aspects may be at the forefront of a person's mind, whereas people who never struggled with dieting might firstly see pleasurable aspects of food. Potentially, certain people, like chronic dieters, might be more prone to context-dependent, food-related mindset fluctuations.

Obesity and Dietary Restraint

We currently face an obesity epidemic. Worldwide, 39% percent of the population is overweight (Body Mass Index (BMI) ≥ 25) or obese (BMI ≥ 30) (WHO, 2020). This is problematic because overweight and obesity are associated with unfavorable health conditions, such as cardiovascular diseases, musculoskeletal disorders, and some cancers (WHO, 2020). Ultimately, overweight and obesity are caused by an imbalance of energy intake and energy expenditure, with energy intake exceeding energy expenditure for a prolonged period (Romieu et al., 2017). The modern "obesogenic" environment contributes to the high overweight and obesity rates by constantly providing easy access to cheap high-caloric hyperpalatable food and by promoting a sedentary lifestyle (Swinburn et al., 2011).

Some people try to counter adverse effects of the obesogenic environment by implementing dietary restraint. Dietary restraint refers to attempts to reduce food intake to control body weight, which results from chronic concerns about body weight and shape (Herman & Polivy, 1980). Paradoxically, dietary restraint is associated with an increased BMI and restrained eaters might be at an increased risk of developing eating pathologies, such as binge eating. Dietary restraint represents an effort to restrict food intake and is in many cases not associated with an objective energy deficit (Stice, Sysko, Roberto, & Allison, 2010). Yet, restrained eaters may limit their food intake in the sense that they consume less than they would like to, and therefore they may feel food deprived. In other words, restrained eaters might eat less than they hedonically want, but not less than they physiologically need (Lowe & Butryn, 2007). Restrained eaters may often experience a conflict between wanting to restrict food intake to manage their weight while also wanting to enjoy food (Stroebe, Mensink, Aarts, Schut, & Kruglanski, 2008; Stroebe, Van Koningsbruggen, Papies, & Aarts, 2013). To achieve their weight management goals, restrained eaters might set themselves dieting rules to control their food intake. The combination of inner ambiguity towards food and dieting rules might result in counterregulatory eating. That is, when restrained eaters are given a high-caloric pre-load, such as ice-cream, which supposedly violates their dieting rules, before a taste test, they consume more food during the taste test than when no pre-load was given. Quite the opposite, unrestrained eaters decrease their food intake after a pre-load compared to with no pre-load (Herman & Mack, 1975). Overall, it appears that restrained eaters are torn between conflicting motivations towards food, which gives rise to altered food approach behavior, such as attentional approach or avoidance of food or counterregulatory eating.

Due to their subjective feeling of deprivation and their conflicting motivations, restrained eaters may perceive food differently than unrestrained eaters. This altered perception of food cues might underlie the problematic eating behavior of restrained eaters. It has been proposed that the altered perception of food is reflected in increased attention for food and increased reward sensitivity (Polivy & Herman, 2017). Increased attention for food may be manifested in an attention bias (AB) for food. AB for food refers to selective attentional processing of food stimuli, including voluntary and involuntary attentional processes (Werthmann, Jansen, & Roefs, 2015). Increased reward sensitivity can be operationalized as increased activity in brain regions related to reward in response to high-caloric palatable foods as compared to control stimuli (Franken & Muris, 2005).

In the present thesis, the idea is tested that brain responses to food and AB for food are dependent on the situational factors as well as characteristics of a person. In particular, we consider effects of mindset or attentional focus (which will be used synonymously in the present thesis), and hunger, as examples of situational factors, and dietary restraint, as an example of an eating-related characteristic of a person. So, the core aim of this thesis is assessing how mindset/attentional focus, hunger, and dietary restraint affect brain responses to food, AB for food, and food intake. This chapter will provide a concise introduction to research on brain responses to food and AB for food in relation to dietary restraint, and will give an outline of research that has already considered effects of mindset/attentional focus and hunger on these processes.

The measurement of brain responses to food

Information about food is thought to be processed by the mesocorticolimbic system of the brain. Activity in these brain regions is based on the neurotransmitter dopamine and is considered to be related to reward processing. The mesocorticolibmic system encompasses several brain structures, including the amygdala, nucleus accumbens, striatum, ventral pallidum, ventromedial prefrontal cortex (vmPFC), orbitofrontal cortex (OFC), and insula. Also, certain brain regions that have been associated with control-related functions, such as the dorsal anterior cingulate cortex (dACC) and dorsolateral prefrontal cortex (dlPFC), belong to the mescorticolimbic system (Berthoud, Lenard, & Shin, 2011; Giuliani, Merchant, Cosme, & Berkman, 2018; Haber & Knutson, 2010; Leigh & Morris, 2018).

Brain responses to food can be measured with functional magnetic resonance imaging (fMRI). In most studies investigating the relation between brain responses to food and dietary restraint, participants in the MRI scanner were shown pictures of (high-caloric palatable) food and pictures of neutral objects. Most often, participants were shown the images during fMRI scanning without a specific task, or with a simple task, such as judging whether the presented stimulus was a food, to ensure that participants were paying attention to the images. In most studies, the data were analyzed using mass-univariate analysis, meaning that the activity level for food pictures and neutral pictures was compared at each individual voxel in the brain, yielding a map of brain regions that showed differences in average activity level between food and neutral stimuli.

Some of the studies that investigated brain responses to food in restrained eaters tested the hypothesis that brain responses to food would reflect the paradoxical eating pattern of restrained eaters that is observed during taste tests. That is, it was tested if restrained eaters showed increased reward-related brain activity in response to food in a satiated state, but decreased reward-related brain activity in response to food in a fasted state. In contrast, unrestrained eaters were expected to show increased reward-related brain activity in response in a fasted state but decreased reward-related brain activity in response to food in a satiated state. For example, Coletta et al. (2009) compared brain activity in response to images of highly palatable vs. moderately palatable food between restrained and unrestrained eaters. When comparing brain activity in response to highly palatable vs. moderately palatable food images in a fed state, they observed increased brain activity in restrained eaters in several brain regions, such as the middle frontal gyrus, superior frontal gyrus and insular cortex. In unrestrained eaters, other brain regions, such as the cingulate gyrus, inferior frontal gyrus, precuneus, and parahippocampal gyrus showed increased activity. When comparing brain activity in response to highly palatable vs. moderately palatable food images in a fasted state, unrestrained eaters showed greater brain activity than restrained eaters in several brain regions, like the superior temporal gyrus and middle frontal gyrus. So, restrained eaters seem to be less responsive to palatable food than unrestrained eaters in a fasted state, and restrained and unrestrained eaters seem to differ in their reaction to palatable food in a fed state.

In contrast, Ely, Childress, Jagannathan, & Lowe (2014) found no significant differences between restrained eaters and unrestrained eaters when comparing brain activity in response to highly palatable vs. moderately palatable food images in a fasted state. When comparing brain activity in response to highly palatable vs. moderately palatable food images in a fed state, restrained eaters displayed increased brain activity in anterior cingulate and middle frontal gyrus compared to unrestrained eaters. This pattern of results has been interpreted as indicating an increased desire for highly palatable food in restrained eaters, especially when they have recently eaten. Born et al. (2011) examined brain activity in response to food liking and wanting and dietary restraint in fasted and fed states. In a fasted state, dietary restraint correlated positively with brain activity related to liking as well as wanting in the nucleus accumbens. In a fed state, dietary restraint correlated negatively with brain activity related to liking in the thalamus, cingulate cortex, amygdala, and striatum. So, it seems that food is more attractive for restrained eaters when they are fasted rather than fed. From these studies it seems that restrained eaters show greater interest in food than unrestrained eaters, but the effect of fasting is unclear.

Other studies that investigated brain responses to food in restrained eaters hypothesized that reward sensitivity would generally be increased in restrained eaters, and that brain responses to food would be higher in restrained than in unrestrained eaters. For example, Wang et al. (2016) examined if restrained eaters display increased activity in reward-related brain regions in response to food stimuli compared to unrestrained eaters. They found increased activity in restrained eaters compared to unrestrained eaters in several brain regions, such as the insula and superior frontal gyrus when contrasting high-caloric against low-caloric food, and in the OFC and superior frontal gyrus among other when contrasting high-caloric food against neutral items. They found increased activity in unrestrained eaters compared to restrained eaters in anterior cingulate cortex and precuneus when contrasting high-caloric food against neutral items. The authors interpreted their findings as hyperactivation in reward-related brain regions and hypoactivation in control-related brain regions in restrained eaters. Similarly, Burger & Stice (2011) hypothesized that restrained eaters show hypersensitivity in brain regions associated with food reward. However, they detected no significant effects of dietary restraint on brain activity level in response to food images (neither when contrasting palatable food with unpalatable food nor when contrasting palatable food with glasses of water). So, from these studies, it is not clear if restrained eaters indeed have increased activity in brain regions associated with reward when confronted with high-caloric food.

Overall, it appears that there are no clear or consistent findings on brain responses to food in restrained eaters. Moreover, different studies have tested quite contradictory hypotheses. That is, some studies expected that brain responses to food in restrained eaters would crucially depend on hunger level, such that restrained eaters only show increased brain responses to food (compared to unrestrained eaters) in a satiated state but not in a fasted state, whereas other studies expected that restrained eaters generally would show increased brain responses to food (compared to unrestrained eaters) independent of hunger level. In the literature on brain responses to food, there is a large variability in the exact paradigms that were employed. The type of stimuli that were contrasted differed between studies (e.g., highly palatable vs. moderately palatable food, high-caloric vs. low-caloric food, or food vs. neutral items). Also, the tasks that were used differed between studies. Some studies used simple tasks, such as judging if the presented stimulus is a food, aimed at focusing participants' attention on the stimuli, whereas other studies presented stimuli without an explicit task. In addition, stimulus presentation times differed widely between studies. This heterogeneity of study designs potentially plays a role in the inconsistency in findings.

The inconsistency in findings on brain responses to food in restrained eaters resembles the inconsistency in findings in healthy-weight individuals as well as in individuals with overweight. Also in this literature, findings vary widely from observing increased brain responses to food in individuals with overweight compared to individuals with healthy weight, observing decreased brain responses to food in in individuals with overweight compared to individuals with healthy weight, or observing no significant differences in brain responses to food between body-weight groups (van der Laan, De Ridder, Viergever, & Smeets, 2011; Ziauddeen, Farooqi, & Fletcher, 2012). Most likely, the idea that there are general, context-insensitive differences in brain responses to food between individuals with overweight and individuals with healthy weight is too simplistic. Other factors may also have a strong influence on brain responses to food and might mask body weight and restraint-related differences (Roefs, Franssen, & Jansen, 2018).

The double-sided nature of high-caloric food

Observed inconsistencies between studies might result from suboptimal study designs and unvalidated assumptions. In particular, many previous studies that used passive viewing designs did not have any control over the mental processes that participants engaged in during food picture viewing. Thus, there is no way of knowing what aspects of food participants were considering while viewing food in the scanner. When using these designs, researchers merely assume that participants automatically focus on hedonic aspects of food while viewing the food pictures. Hence, researchers assumed that participants evaluated the tastiness, the reward value, of food stimuli. Based on this assumption, researchers then interpreted increased brain activity in certain brain regions in response to food stimuli as being reward related. So, the type of reasoning used in these studies is based on reverse inference (Poldrack, 2006, 2011). That is, the presence of a mental process is inferred from observed brain activity. To do so, associations between activity in a brain region and mental functions that have been reported in the literature are used as logical basis. Often, one of several mental processes that an area has been associated with is chosen and it is concluded that participants must have engaged in this mental process during scanning because previous studies have linked activity in the observed brain areas with it. However, this reasoning is inductively invalid. Many brain regions are associated with different mental functions and inferring which of those functions was performed cannot be inferred backwards. For example, the insula is one of the regions which is frequently observed as activated and has been associated with many different mental functions (Yarkoni, Poldrack, Nichols, Van Essen, & Wager, 2011). To make valid connections between mental processes and active brain areas, one needs to know the mental process that the participant engages in during scanning. So, it requires tight experimental control over the mental processes, preferably via an experimental task. With knowledge about the mental processes one can make conclusions about the functions of activated brain areas (i.e., forward inference). Moreover, the assumption that participants solely focus on hedonic aspects of food is most likely not true. Today's society is characterized by contradictory views on food. Enjoyment of high-caloric food is emphasized while also perfect body shape and health are idealized. So, in today's affluent food environment, the pleasure or energy content derived from food consumption are presumably not the only aspects people will consider when making food choices. Also, health-related aspects most likely play a role when considering food. The particular aspects of a food that people consider during food decision making probably also depend on the situational context.

Importantly, the mental processes taking place when viewing food stimuli might crucially affect the way food stimuli are perceived and the brain response that is elicited. More specifically, high-caloric palatable food has a double-sided nature, meaning that it has a high hedonic value, because its consumption is pleasurable, but has a low health value, since its overconsumption leads to weight gain and detrimental health outcomes (Roefs et al., 2018). So, the focus of attention likely fluctuates between hedonic and health-related properties of food items, and in this way, participants might alternate between being in a hedonic mindset or being in a health mindset. In a study, this fluctuation may take place within a participant as well as between different participants, hampering the interpretation of the results and prohibiting clear conclusions. Especially restrained eaters, who have conflicted attitudes and goals with respect to food (Stroebe et al., 2013; Urland & Ito, 2010), might fluctuate in their way of looking at food. In a passive viewing design, researchers use no task to control mental processes and therefore cannot know the mental processes that participants engage in during the experiment. Therefore, they have no means of obtaining knowledge of these fluctuations and thus cannot explain varying brain responses to food.

The current thesis takes the double-sided nature of high-caloric palatable food into account by manipulating the attentional focus or mindset that participants engage in when viewing food stimuli. We will do so by using suitable experimental manipulations/tasks to exert tight experimental control over the mental processes that participants engage in during food viewing. In this way, we will be able to use forward inference to obtain valid interpretations of the observed brain activity. We assess the effect that attentional focus or mindset has on brain responses to food that varies in palatability and caloric content, and AB for food. In addition, we assess if the effects of attentional focus or mindset depend on the level of dietary restraint of the participant.

Mass-univariate analyses versus multi-voxel pattern analyses of fMRI data

Mass-univariate analysis, which has been used in most previous studies on brain responses to food, is aimed at detecting differences in regional *average* activation. In this type of analysis, each voxel is analyzed in isolation and the data are spatially smoothed to enhance sensitivity to detect average activation across a group of voxels. Therefore, this analysis approach cannot reveal information that might be contained in more fine-grained multi-voxel activation *patterns*. So, previous studies might have not been able to detect effects that are present only in those more fine-grained patterns. These more fine-grained patterns can be revealed by multi-voxel pattern analysis (MVPA). This analysis technique analyzes the pattern of activity across a set of voxels, thereby taking patterns distributed across voxels into account, and does not rely on spatial smoothing. Therefore, it is sensitive to a wider range of effects, meaning it can detect activity differences that are only apparent when considering patterns besides detecting differences in average activity level of a brain region (Haxby, 2012; Mur et al., 2009). So, by using MVPA one might be able to uncover more fine-grained representations of food in the brain.

It has been observed in earlier empirical studies that positive and negative stimuli elicit similar *levels* of brain activity in OFC when tested with univariate analysis methods. In contrast, by using MVPA, information about stimulus valence (positive vs. negative) could be obtained from multi-voxel activation patterns in OFC. This suggests that valence is represented in a distributed fashion in the OFC, and not reflected in the average level of brain activity (Chikazoe, Lee, Kriegeskorte, & Anderson, 2014). Importantly, it was found that food value is also coded in multi-voxel activity patterns in the OFC. Overall food value could be decoded from medial OFC while food attributes, like carbohydrate and fat, that constitute food value could be decoded from lateral OFC. This suggests that information about food value and nutritive attributes is contained in multi-voxel activity patterns and is represented in a distributed fashion in the brain (Suzuki, Cross, & O'Doherty, 2017). In line with these findings, an earlier study from our laboratory observed no significant differences in the level of brain activity between individually tailored palatable and unpalatable food stimuli. Food palatability could instead be decoded from several brain regions with multi-voxel pattern analysis. This also suggests that information about palatability was only contained in multi-voxel activity patterns but not in average activity level and suggests that food palatability might also be coded in a distributed fashion by the brain (Franssen, Jansen, van den Hurk, Roebroeck, & Roefs, 2020). In addition, it was found that palatable and unpalatable food items do not differ in average activity level, though they differ highly in value but are equally salient. However, because it was possible to decode food value and palatability from multi-voxel activity patterns, it seems the value of food items or specific characteristics such as palatability are likely represented in multi-voxel activity patterns. So, MVPA is likely needed to truly understand how the brain represents food. In the current thesis, we will also employ MVPA to gain a deeper understanding of how the brain processes information about food attributes, such as palatability and calorie content.

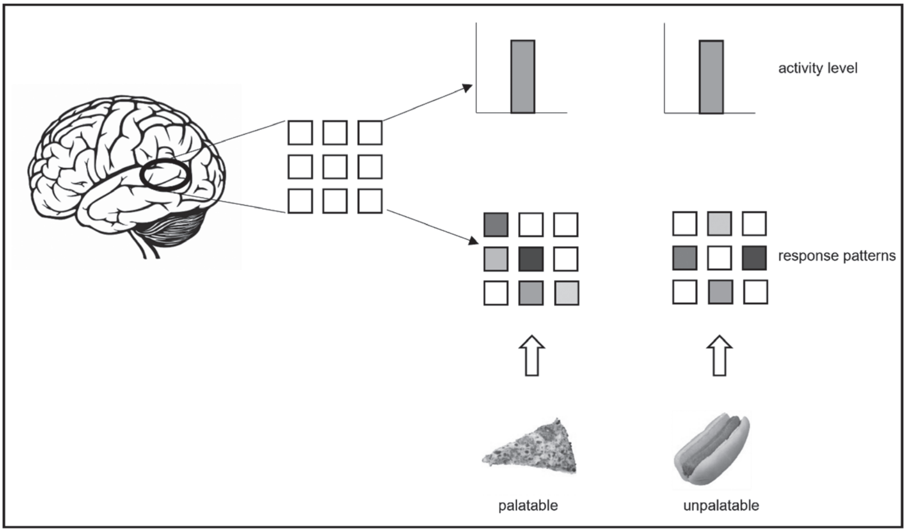

Figure 1: This figure illustrates the difference between univariate analysis and MVPA. It shows hypothetical activity levels and patterns in response to two different example food stimuli (palatable and unpalatable) which might yield the same average activity level but different activity patterns. It highlights that a brain region can display similar activity levels to stimuli while the pattern of activations across voxels can differ substantially. Therefore, MVPA might be sensitive to more subtle differences in brain activity than univariate analysis. The figure is based on Figure 1 by Mur, Bandettini, & Kriegeskorte (2009).

Paradigms to measure AB for food

AB for food has been measured in several ways. AB can be measured indirectly, through the assessment of manual response latencies, or directly via eye-movement recordings. The most employed tasks are the food Stroop task, the visual probe task, and the visual search task (Hardman et al., 2021; Werthmann et al., 2015). In the food Stroop task, participants are required to indicate the color of a food or a neutral word as quickly as possible, ignoring the meaning of the words (Overduin, Jansen, & Louwerse, 1995; Stroop, 1935; Williams, Mathews, & MacLeod, 1996). AB scores are calculated by subtracting average response latency on trials with neutral words from trials with food words. A longer response latency on trials with food words compared to trials with neutral words is indicative of an AB for food. A drawback of the Stroop task is that more interference by food stimuli, as manifested in longer reaction times, does not necessarily reveal an AB for food as there are other cognitive processes that could underlie the observed interference, such as avoiding attending food words which could also lead to prolonged response latencies (Werthmann et al., 2015).

In the food version of the visual probe task (Mogg, Bradley, De Bono, & Painter, 1997; Mogg, Bradley, Hyare, & Lee, 1998), a food picture is presented on one side of the screen while a neutral picture is presented on the other side of the screen, for a certain duration (e.g., 500 ms or 1500 ms). After this period, the pictures disappear from the screen and a probe, such as a dot, appears in the position of one of the images. The participant must indicate the position of the probe as quickly as possible (MacLeod, Mathews, & Tata, 1986). AB scores are calculated by subtracting response latencies on trials in which the probe appeared in the position of the food picture from trials in which the probe appeared in the position of the neutral picture. A positive bias score reflects an AB for food, whereas a negative bias score reflects an AB away from food.

In the visual search task, participants are presented with search matrices consisting of stimuli from one category and an odd-one out stimulus form another category. Participants must detect the odd-one-out stimulus as quickly as possible (Rinck, Becker, Kellermann, & Roth, 2003; Smeets, Roefs, van Furth, & Jansen, 2008). Matrices can consist of neutral stimuli with a food odd-one-out stimulus, or of food stimuli with a neutral odd-one out stimulus, or neutral stimuli with a neutral odd-one out stimulus (from the other neutral category). Speeded detection of food stimuli can be investigated by subtracting response latencies on neutral matrices with a neutral odd-one-out stimulus from response latencies on neutral matrices with a food odd-one-out stimulus. Negative scores indicate speeded detection of food stimuli. Increased distraction by food stimuli can be examined by subtracting response latencies on neutral matrices with a neutral odd-one-out stimulus from response latencies on food matrices with a neutral odd-one-out stimulus. Positive scores indicate increased distraction by food.

Less often used paradigms include the flanker task (Eriksen & Eriksen, 1974), the rapid serial visual presentation task (Potter, 1984), and the exogeneous cuing task (Posner, 1980). Very briefly, in the flanker task a centrally presented target is flanked by distractor stimuli (flankers) which are congruent or incongruent in response key to the target. In this way, effects related to response conflict can be assessed. In the rapid serial visual presentation task, a stream of images is presented, and the participant must report the occurrence of a target picture. This paradigm is often used to study the attentional blink, describing a period of limited ability to deploy attention. In the exogenous cueing task, which is used to study covert attention, a cue is presented which either validly or invalidly predicts the location of a subsequently presented target.

AB for food in restrained eaters?

There is some evidence for an AB for food, mostly for high-caloric food, in restrained eaters. That is, in a study using a rapid serial visual presentation task, it was found that restrained eaters indeed display a temporal AB for high-caloric food (Neimeijer, de Jong, & Roefs, 2013). A study using a modified Stroop task also indicated that restrained eaters display a greater AB for food than unrestrained eaters (Hotham, Sharma, & Hamilton-West, 2012). One study employed a visual search task to investigate AB for food in restrained eaters (Hollitt, Kemps, Tiggemann, Smeets, & Mills, 2010). Results suggest that restrained eaters display approach-avoidance behavior towards food, meaning that restrained eaters show faster detection of food stimuli but also faster disengagement from food stimuli than unrestrained eaters. However, upon careful inspection of the graphs, it appeared that the differences between restrained and unrestrained eaters were mainly based on a slower responding to neutral stimuli by restrained eaters instead of on differences in responding to food stimuli.

In contrast, other studies did not find evidence of a food AB in restrained eaters (Ahern, Field, Yokum, Bohon, & Stice, 2010; Boon, Vogelzang, & Jansen, 2000; Veenstra, de Jong, Koster, & Roefs, 2010; Werthmann et al., 2013; Wilson & Wallis, 2013). For example, in an exogenous cueing task, participants displayed attentional avoidance of food stimuli, but this was the case for restrained as well as unrestrained eaters (Veenstra et al., 2010). By using a visual probe task, evidence for an AB for food was found in all participants, but no significant differences between restrained and unrestrained eaters were detected (Ahern et al., 2010; Werthmann et al., 2013). Yet, another study using a visual probe task found no evidence of AB for food in all participants, and similarly yielded no differences between restrained and unrestrained eaters (Boon et al., 2000). Likewise, an AB for food in all participants, with no differences between restrained and unrestrained eaters, was detected by using a modified Stroop task (Wilson & Wallis, 2013). Overall, it appears that evidence for an AB for food in restrained eaters is inconclusive (Roefs, Houben, & Werthmann, 2015; Werthmann et al., 2015). Similarly, a meta-analysis investigating AB for food in restrained eaters yielded inconclusive results, with some analyses observing a small effect of dietary restraint on AB for food (Brooks, Prince, Stahl, Campbell, & Treasure, 2011) and others detecting no significant effect of dietary restraint on AB for food (Dobson & Dozois, 2004; Johansson, Ghaderi, & Andersson, 2005; Watson & Le Pelley, 2021).

Of course, one reason for the inconsistent results can be the large variety in the paradigms that were used to measure AB for food, and the differences in exact parameters, such as type of stimuli, stimulus presentation durations, type of control stimuli, etc. So, different paradigms might measure different aspects of AB for food, which could be difficult to reconcile. In addition, previous tasks most often required participants to focus on food items. Thereby, these studies might differ from attention processes that do not play a role in distraction by food that takes place in daily life. That is, in daily life people tend to get distracted by food while being busy with other tasks without having the intention to think about food. So, how can AB for food best be measured?

A more ecologically valid paradigm to assess AB for food might be the additional singleton paradigm (Theeuwes, Kramer, Hahn, & Irwin, 1998), which has been developed to assess attentional capture by completely irrelevant salient stimuli, called distractors. In this paradigm, the distractor is presented in peripheral vision and does not share any features (e.g., location) with the response target. So, the distractor is completely irrelevant to the task. Therefore, this paradigm might be more suitable to study distraction in real-life situations, in which irrelevant food stimuli capture attention. One could argue that in most situations in which an AB for food could negatively affect food-related decision making, food is not a core feature of situation but rather invades the mind of a person who is busy with another task. However, in previously used paradigms studying AB for food, food items always shared features with the relevant response target of the participant (e.g., both were presented in the same location in central vision), in that processing them was indirectly necessary for correct task performance (Cunningham & Egeth, 2018; Forster & Lavie, 2011). The central focus on food items might make these paradigms less ecologically valid. Using a completely irrelevant food distractor in the additional singleton paradigm might increase the ecological validity of the task used to assess AB for food, as food items that negatively interfere with attention are rarely present in the central focus of a person.

In this thesis, we employ a modified version of the additional singleton paradigm to study AB for food. The task display consists of six grey circles, which are equally spaced around an imaginary circle. Each circle contains a small number. A small fixation cross is positioned in the middle of the imaginary circle and the participant is instructed to fixate. After a predetermined amount of time, five of the six circles change color and the small numbers inside the circles change to letters. The participant is instructed to make an eye-movement to the circle that did not change color, the target, and indicate the identity of the letter inside the target with a button press. On a certain percentage of trials, a completely irrelevant distractor, either a food or a neutral picture, is added to the display at the time of color change. The participant is told that she can ignore the distractor. Food stimuli thus served as distractors and were completely irrelevant for task performance in this paradigm. The irrelevance of food stimuli in the additional singleton task distinguishes this paradigm from other paradigms that previously have been used to study AB for food in restrained eaters.

Empirical evidence for effects of mindset on brain responses to food an AB for food

Several studies investigated effects of cognitive factors, such as mindset or attentional focus, on food perception. One study tested if self-regulation strategies (upregulation of palatability thoughts, cognitive reappraisal, suppression palatability thoughts) affect food craving and brain activity in the mesocorticolimbic system (Siep et al., 2012). It was observed that upregulation increased craving and increased activity in the mesocorticolimbic system, such as the posterior insular gyrus and the medial OFC. No significant difference in craving between cognitive reappraisal and thought suppression was detected. Yet, thought suppression yielded stronger decreases of activity level in the mesocorticolimbic regions than cognitive reappraisal. Similarly, another study observed effects of task instructions on brain responses to food (Frankort et al., 2012). Overweight and healthy weight participants were presented with pictures of food and were instructed to focus on the taste of the food or received no specific instructions. Greater activity in overweight participants than in healthy weight participants was observed during taste imagination in several brain regions associated with food reward, whereas the opposite pattern was observed when no viewing instructions were given, ergo effects of BMI interacted with mindset in their effect on brain responses to food. So, it seems that mindset is an influential factor on how food is perceived.

Interestingly, it has been shown that mindset affects which brain regions respond to food stimuli. For example, participants have been instructed to focus on health or taste while they had to make decisions on snack foods (Bhanji & Beer, 2012). It was found that some brain areas were related to food decisions independent of mindset (e.g., medial OFC), whereas other areas were related to food decisions only in the health mindset (e.g., lateral prefrontal cortex (PFC)) or in the taste mindset (e.g., left amygdala). This suggests that the way the brain responds to food depends at least partly on mindset. Another study tested if a hedonic compared to a neutral attentional focus influenced neural responses to individually tailored palatable and unpalatable high-caloric food stimuli (Franssen et al., 2020). It was found that activity was increased in a hedonic attentional focus compared to a neutral attentional focus. Importantly, activity level did not differ between palatable and unpalatable food stimuli. Considering that palatable and unpalatable food items differ in rewarding value but not in salience, and assuming that food is more salient in a hedonic than in a health attentional focus, these findings suggest that the observed activity levels could reflect salience of food stimuli instead of reward value. This interpretation conflicts with interpretations of results from previous studies, which interpreted increased brain activity level in response to food as being reward-related (LaBar et al., 2001; Martin et al., 2010; Rothemund et al., 2007). However, almost no previous studies contrasted palatable and unpalatable food directly but rather contrasted food with neutral stimuli, and therefore were not able to distinguish salience from palatability.

Mindset not only influences brain activity, but also portion size decisions. It was observed that participants chose reduced portion sizes compared to baseline in a health and in a pleasure mindset. In contrast, participants chose larger portion sizes in a fullness mindset. The health mindset was associated with increased activity in left dlPFC, whereas the pleasure mindset was associated with increased activity in left OFC. The fullness mindset was associated with increased activity in left posterior insula (Hege et al., 2018; Veit et al., 2020). This suggests that a health mindset could lead to more control processes in food related situations than a hedonic or a fullness mindset. Overall, it appears that mindset plays a crucial role in the way the brain responds to food, and thereby also affects food decisions, as is seen by its influence on portion size choices.

Interestingly, effects of mindset on AB for food have also been observed (Werthmann et al., 2016). Using a visual probe task, it was observed that a health mindset attenuated AB for food compared to palatability mindset particularly in restrained eaters. Overall, it appears that mindset is a decisive factor in how food is perceived, how the brain responds to it, and how much attention food attracts. Importantly, it seems that neural responses to food and AB for food are not stable characteristics of a person but are affected by fluctuations of cognitive states and depend on the situational context (Field et al., 2016; Hardman et al., 2021; Roefs et al., 2018).

Empirical evidence for effects of hunger on AB for food

Also, hunger might play a role in determining AB for food. It has been observed that hunger increases attractiveness of food (Cabanac, 1971). In addition, it has been observed that hunger increases craving for food, and thereby likely influences food-related perception (Reents, Seidel, Wiesner,

& Pedersen, 2020). Interestingly, several studies observed an increased AB for food in a hungry compared to a satiated state (e.g., Jonker, Bennik, de Lang, & de Jong, 2020; Loeber, Grosshans, Herpertz, Kiefer, & Herpertz, 2013; Piech, Pastorino, & Zald, 2010). However, not all studies observed an effect of hunger on AB for food (e.g., Ruddock, Field, Jones, & Hardman, 2018). Interestingly, one study observed that only hungry individuals were faster at detecting high-caloric than low-caloric food but not satiated individuals. Yet, no differences between satiated and fasted individuals were observed for detecting food and non-food stimuli. So, effects of hunger might also depend on the type of food (Sawada, Sato, Minemoto, & Fushiki, 2019). A recent meta-analysis suggests that state variables, such as hunger, have more influence on AB for food than trait-like variables such as dietary restraint (Hardman et al., 2021). Overall, it appears that attention to food varies on a situational basis and might not be a characteristic associated with more stable eating traits like chronic dietary restraint. Nevertheless, it has been observed that the specific type of attentional interference of food caloric value differs between restrained and unrestrained eaters, but only in a hungry state (Forestell, Lau, Gyurovski, Dickter, & Haque, 2012). Taken together, it appears that effects of state (hunger, mindset/attentional focus) and trait (dietary restraint) might interact in their influence on AB for food.

This thesis

The overall aim of the current thesis is assessing the effects of mindset/attentional focus and hunger (state variables), and dietary restraint (trait variable) on brain responses to food, AB for food, and food intake. More specifically, we hypothesize that brain responses in the mesocorticolimbic system will be highest in response to high-caloric palatable food, especially in a hedonic attentional focus. We expect that attentional focus dependent differences in brain responses to food will be most apparent in participants with high levels of dietary restraint. Furthermore, we hypothesize AB for food will be stronger and food intake will be higher in a hedonic than in a health mindset, and that effects of mindset will be most pronounced in participants with high levels of dietary restraint. In addition, we expect that participants with high levels of dietary restraint will show increased

AB for food, particularly in a hungry state. To test our hypotheses, we use measurements of eye-movements and manual response latencies as indicators of attentional bias for food, caloric intake during a bogus taste test, and brain activity measurements with fMRI in response to food stimuli, which we analyze with mass-univariate analysis as well as MVPA. In the following, I will outline the chapters of the current thesis.

Chapter two of this thesis is concerned with studying effects of attentional focus and dietary restraint on brain responses to food. To do so, we measure brain activity of participants with fMRI while they are presented with images of individually tailored palatable and unpalatable, high-caloric and low-caloric visual food stimuli. A fast-paced one-back task is used to manipulate attentional focus to be hedonic, health or neutral. We hypothesize that the level of brain activity will be strongly influenced by attentional focus. In particular, we expect that a hedonic attentional focus will lead to more involvement of brain regions like the ventral striatum or the OFC, whereas a health attentional focus will elicit more involvement of brain regions like the dlPFC or the dACC. Furthermore, we expect that effects of attentional focus will be most pronounced in participants scoring high on dietary restraint. We expect that palatability and calorie content will be represented in patterns of brain activity. We expect that decoding accuracy of palatability will be highest in the hedonic attentional focus whereas decoding accuracy of calorie content will be highest in the health attentional focus. In addition, we expect that the hypothesized effects will be most pronounced in participants scoring high on dietary restraint.

Chapter three of this thesis assesses effects of mindset and dietary restraint on AB for food and food intake. Therefore, we manipulate mindset to be either health or hedonic and measure eye-movements and manual response latencies while participants performed a modified additional singleton task in which high-caloric food stimuli and neutral stimuli serve as irrelevant distractors. In addition, food intake was measured during a bogus taste test. We expect that participants will display a larger AB for food in the hedonic than in the health mindset. We also expect increased food intake in the hedonic compared to the health mindset. We expect that effects of mindset will be most pronounced in participants scoring high on dietary restraint.

Chapter four of this thesis investigates effects of hunger and dietary restraint on AB for food and food intake. For this purpose, we manipulate hunger and assess AB for high-caloric and low-caloric food with a visual search task in which high-caloric and low-caloric food words, and neutral words are presented in search matrices while manual response latencies of target detection are recorded. We also measure caloric intake from high-caloric and low-caloric food during a bogus taste test. We hypothesize that participants with high levels of dietary restraint will display a larger AB for (high-caloric) food than participants with low levels of dietary restraint, especially in a hungry state.

Chapter five will provide a summary of the main findings and conclusions of this dissertation. Furthermore, it will provide an outlook on implications of the current findings and directions for future research.

2

CHAPTER 2

It Is a Matter of Perspective: Attentional Focus Rather Than Dietary Restraint Drives Brain Responses to Food Stimuli

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Abstract

Brain responses to food are thought to reflect food's rewarding value and to fluctuate with dietary restraint. We propose that brain responses to food are dynamic and depend on attentional focus. Food pictures (high-caloric/low-caloric, palatable/unpalatable) were presented during fMRI-scanning, while attentional focus (hedonic/health/neutral) was induced in 52 female participants varying in dietary restraint. The *level* of brain activity was hardly different between palatable versus unpalatable foods or high-caloric versus low-caloric foods. Activity in several brain regions was higher in hedonic than in health or neutral attentional focus ($p < 0.05$, FWE-corrected). Palatability and calorie content could be decoded from multi-voxel activity patterns ($p < 0.05$, FDR-corrected). Dietary restraint did not significantly influence brain responses to food. So, *level* of brain activity in response to food stimuli depends on attentional focus, and may reflect salience, not reward value. Palatability and calorie content are reflected in *patterns* of brain activity.

Keywords: food, palatability, calorie content, attentional focus, dietary restraint, fMRI, MVPA

Introduction

We live in an obesogenic environment, which is characterized by the pervasive presence of cheap, easily obtainable high-caloric palatable food, and a predominantly sedentary lifestyle (Poston II & Foreyt, 1999). This excessive supply of high-caloric food can easily lead to a positive energy balance (Stubbs & Lee, 2004). Consequently, the prevalence of overweight and obesity has increased rapidly (Swinburn et al., 2009; WHO, 2020). Given this development, many people attempt to control their body weight by dieting (Slof-Op 't Landt et al., 2017). Chronic dieting attempts to reduce or maintain body weight are referred to as dietary restraint (Herman & Polivy, 1980). However, long-lasting weight reduction by dietary restraint appears to be difficult (Fildes et al., 2015). Restrained eaters tend to struggle with weight gain and often have a higher body-mass-index (BMI) than unrestrained eaters (Snoek, van Strien, Janssens, & Engels, 2008). Relatedly, restrained eaters are prone to overeating, and cognitive processes and food cue reactivity might be more important in determining eating behavior of restrained eaters than internal ingestion signals (Herman & Polivy, 1984; Jansen, Schyns, Bongers, & van den Akker, 2016). The current study aims to examine if this responsiveness to high-caloric foods of restrained eaters is consistently reflected in brain responses to food.

In the past decade, researchers have examined brain responses to food stimuli in restrained eaters (Born et al., 2011; Burger & Stice, 2011; Coletta et al., 2009; Demos, Kelley, & Heatherton, 2011; Ely, Childress, Jagannathan, & Lowe, 2014; Su, Bi, Gong, Jiang, & Chen, 2019; Wang et al., 2016; Wood et al., 2016). Several studies tested hypotheses related to the paradoxical eating patterns of restrained eaters that are observed in behavioral experiments. That is, restrained eaters increase their food intake after consumption of a high-caloric preload (e.g., a milkshake), but consume less than unrestrained eaters in a no-preload control condition (Herman & Mack, 1975). Overall, these studies hypothesized that restrained eaters would show increased reward-related brain activity (compared to unrestrained eaters) in a satiated state, that is when a preload was given, but decreased reward-related brain activity (compared to unrestrained eaters) in a hungry state, that is when no preload was given (Born et al., 2011; Coletta et al., 2009; Demos et al., 2011; Ely et al., 2014). For example, Coletta et al. (2009) observed increased brain activity in unrestrained eaters compared to restrained eaters in a fasted state in several brain regions, like the superior temporal gyrus and middle frontal gyrus. In contrast, in a fed state, they observed increased brain activity in restrained eaters in certain brain regions, like the middle frontal gyrus, superior frontal gyrus and insular cortex, whereas unrestrained eaters showed greater brain activity in other areas like the cingulate gyrus, inferior frontal gyrus, precuneus, and parahippocampal gyrus. In contrast, Ely et al. (2014) observed no significant differences between restrained eaters (who they called historical dieters) and unrestrained eaters (who they called non-dieters) in a fasted state. In fed state, they only observed increased brain activity in restrained eaters compared to unrestrained eaters in anterior cingulate and middle frontal gyrus. Born et al. (2011) specifically investigated the relationship between brain activity in response to food liking and wanting and dietary restraint in fasted and fed states. They found that dietary restraint correlated positively with brain activity related to liking as well as wanting in the nucleus accumbens when participants were in a fasted state. In contrast, in a fed state, dietary restraint correlated negatively with brain activity related to liking in the thalamus, cingulate cortex, amygdala, and striatum. Overall, these studies show quite some variability in the exact pattern of differences that are observed between restrained and unrestrained eaters. In addition, the specific brain regions detected in these studies show moderate overlap at best.

Other studies on the effect of dietary restraint on brain responses to food generally expected increased reward sensitivity in restrained eaters as compared to unrestrained eaters. For example, Wang et al. (2016) investigated if restrained eaters would show increased activity in reward-related brain regions in response to high-caloric and low-caloric food stimuli compared to unrestrained eaters. They found increased activity in restrained eaters compared to unrestrained eaters in several brain regions when contrasting high-caloric with low-caloric food (e.g., in insula and superior frontal gyrus), when contrasting high-caloric food with neutral stimuli (e.g., in orbitofrontal cortex and superior frontal gyrus), and when contrasting low-caloric food with neutral stimuli (in left superior parietal gyrus and superior temporal gyrus). They found increased activity levels in unrestrained eaters compared to restrained eater only when contrasting high-caloric food with neutral stimuli (in anterior cingulate cortex (ACC) and precuneus). Burger & Stice (2011) also hypothesized that restrained eaters would show hypersensitivity in brain regions associated with food reward. However, they found no effect of dietary restraint on brain responses to pictures of appetizing food. Dietary restraint only affected brain responses to actual food receipt in their study. Notably, these studies do not provide consistent evidence for increased reward sensitivity in restrained eaters either.

Taken together, the studies on differences in brain responses to food between restrained and unrestrained eaters do not provide a clear picture. Different studies have tested contradictory hypotheses and the variability between study results is large (Born et al., 2011; Burger & Stice, 2011; Coletta et al., 2009; Demos et al., 2011; Ely et al., 2014; Su et al., 2019; Wang et al., 2016; Wood et al., 2016). The inconsistency in findings in this field may be partly due to small sample sizes (Born et al., 2011; Burger & Stice, 2011; Coletta et al., 2009; Ely et al., 2014; Wang et al., 2016; Wood et al., 2016) and/or lenient thresholding (Coletta et al., 2009; Ely et al., 2014). The divergence in findings resembles the divergence in findings on brain responses to food stimuli in healthy-weight individuals, which have been described as moderately convergent at best by a meta-analysis (van der Laan, de Ridder, Viergever, & Smeets, 2011), as well as the inconsistency in brain responding to food stimuli in obese people (Morys, García-García, & Dagher, 2020; Ziauddeen, Farooqi, & Fletcher, 2012).

Divergent findings might partly be caused by differing task instructions and paradigms across studies. In particular, previous neuroimaging studies either employed a passive viewing paradigm, in which participants are asked to look at food stimuli without further instructions, or used simple instructions, such as indicating whether the presented stimulus is a food, to ensure deliberate processing of food stimuli (Burger & Stice, 2011; Demos et al., 2011; Ely et al., 2014; Ziauddeen et al., 2012). In this way, no experimental control is exerted over the mental processes that participants engage in while viewing food stimuli. Instead, the mental processes that participants engage in, like experiencing feelings of reward, are merely assumed or inferred from the repertoire of cognitive functions that the discovered brain regions have been associated with before in the literature. However, the latter logic is based on reverse inference – that is, inferring mental function from brain activity – and is unlikely to be valid (Poldrack, 2006, 2011). Importantly, high-caloric palatable food can evoke ambiguous feelings. Its taste is highly pleasurable, yielding a high hedonic value, yet its consumption is associated with negative health outcomes, like weight gain, yielding a low health value. Depending on the internal state of an individual or on situational factors, an individual might focus on either hedonic or health-related aspects of food stimuli. Therefore, it is likely that mental processes in response to viewing high-caloric palatable food vary within and across individuals, depending on the attentional focus that a person endorses (Roefs, Franssen, & Jansen, 2018; Siep et al., 2012).

Mental processes are reflected in brain responses measured by functional magnetic resonance imaging (fMRI). Recently, it has been shown that specific brain activations crucially depend on the *interpretation* of a stimulus (Yeshurun et al., 2017). Furthermore, it has been demonstrated that the type of task (edibility vs. color judgements) that participants perform, influences the brain response to food stimuli (Pohl, Tempelmann, & Noesselt, 2017). Relatedly, considering the ambivalent nature of high-caloric palatable food, the attentional focus of a person is a crucial factor influencing the brain activation to food stimuli. It has been shown that the attentional focus plays a role in determining brain responses to food stimuli, such that a hedonic attentional focus results in different brain responses to food stimuli than a health attentional focus (Bhanji & Beer, 2012; Frankort et al., 2012; Franssen, Jansen, van den Hurk, Roebroeck, & Roefs, 2020; Hare, Malmaud, & Rangel, 2011; Hege et al., 2018; Roefs et al., 2018; Siep et al., 2012). Effects of attentional focus might even outweigh effects of stimulus characteristics. As such, it has been observed that several regions of the mesocorticolimbic system showed increased activation to food stimuli when participants engage in a hedonic attentional focus compared to a neutral attentional focus, whereas no differential level of activation could be detected between palatable and unpalatable food stimuli (Franssen et al., 2020).

In addition, analysis methods might have a share in ambiguous research results. More commonly used univariate analysis techniques might be less sensitive than multivariate analysis techniques (Haxby, 2012; Kragel, Carter,

& Huettel, 2012). Interestingly, it has been shown that positive and negative valence cannot be significantly distinguished by univariate analysis techniques, whereas it is possible to distinguish between positive and negative valence by multivariate analysis techniques (Chikazoe, Lee, Kriegeskorte, & Anderson, 2014). Similarly, it appears that information about value is contained in multi-voxel activity patterns in the orbitofrontal cortex (OFC) (Howard, Gottfried, Tobler, & Kahnt, 2015; Yan et al., 2016). More specifically, food value could be decoded from multi-voxel activity patterns in the orbitofrontal cortex (Suzuki, Cross, & O'Doherty, 2017). In addition, food preference and choice could be predicted from multi-voxel activity patterns (Pogoda, Holzer, Mormann, & Weber, 2016; van der Laan, De Ridder, Viergever, & Smeets, 2012). Similarly, it is possible to decode palatability of food stimuli, especially when participants engage in a hedonic attentional focus (Franssen et al., 2020). So, food characteristics, such as palatability or calorie content might be reflected in patterns of brain activity rather in the level of brain activity.

The current study investigates the effects of attentional focus, palatability, and calorie content on brain responses to food stimuli in healthy-weight women varying in dietary restraint using fMRI. Three attentional foci are employed: a hedonic attentional focus, a health attentional focus, and a neutral attentional focus. The hedonic attentional focus is conceptualized as a focus on taste properties of food. The health attentional focus is conceptualized as a focus on the calorie content, as an example of a health-related property of food. The neutral attentional focus is conceptualized as focus on color, as an example of a neutral, non-ingestion-related property of food. Attentional focus is manipulated by a fast-paced one-back task (comparable to the task used by Franssen et al., 2020), in which participants are asked to compare subsequent food images, either on taste (hedonic attentional focus), calorie content (health attentional focus), or color (neutral attentional focus). The presented food stimuli are individually tailored on palatability and comprise palatable and unpalatable, high-caloric and low-caloric food. The current study builds on the findings of Franssen et al. (2020), and extends their findings by testing the effects in healthy-weight participants and by assessing the effects of calorie content and dietary restraint, and by adding a health attentional focus.

We hypothesize that attentional focus in interaction with dietary restraint determines brain responses to food. We predict that a hedonic attentional focus will lead to more involvement of brain regions like the ventral striatum or the OFC, while a health attentional focus will elicit more involvement in brain regions like the dorsolateral prefrontal cortex (dlPFC) or the ACC. Furthermore, we expect that palatability and calorie content are represented in multi-voxel activity patterns. We expect that decoding accuracy of palatability will be higher in the hedonic than in the health attentional focus, and that decoding accuracy of calorie content will be higher in the health than in the hedonic attentional focus. We expect that these effects will be more pronounced in participants scoring high on dietary restraint. We use standard mass-univariate analysis as well as multi-voxel pattern analysis (MVPA) to test these hypotheses.

Methods

Participants

Participants were recruited via advertisements on university notification boards, social media, and the university's student research participation system. All participants were screened before participating to check study eligibility, excluding participants with MRI safety issues or neurological illnesses. In total, 63 healthy right-handed female volunteers took part in the study. Eleven participants were excluded from analyses due to the following reasons: one participant had to be excluded due to technical problems with the scanning sequence, one participant felt sick in the scanner and quit during the first run, one participant could not enter the scanner due to a not previously reported non-removable metallic object, and eight participants were excluded afterwards due to excessive head movement (exceeding 3 mm/degree in any direction). The final sample consisted of 52 participants (BMI: M = 22.15, SD = 1.91; age: M = 22.13 years, SD = 3.13; dietary restraint: M = 13.92, SD = 5.00). The study was approved by the Ethical Committee of the Faculty of Psychology and Neuroscience of Maastricht University and each participant gave written informed consent prior to participation. The participant either received a gift voucher of €25 or course credits as compensation and were debriefed after the study. The study was pre-registered on AsPredicted (https://aspredicted.org/blind.php?x=/M51_64S).

Materials and assessments

Restraint Scale

Each participant's level of dietary restraint was assessed by an online questionnaire approximately one week before the study. The online questionnaire encompassed the eleven items of the revised restraint scale (Herman & Polivy, 1980), which were intermixed with distractor items to obscure the purpose of the questionnaire. Lifestyle-related questions, like "How many hours do you sleep per night on average?", were used as distractor items. The restraint scale had acceptable internal consistency in the current sample (Cronbach's α = 0.76).

Hunger assessment

To standardize hunger level, the participant was asked to eat something small (e.g., a sandwich) 2 hours before participation, and thereafter refrain from eating and drinking anything except water. The participant was asked to fill a form about the time of their last meal and to describe what they had eaten. Hunger level was assessed with the question: "How hungry do you feel at this moment?", on a 100 mm visual analogue scale (VAS) ranging from 0 (not hungry at all) to 100 (very hungry).

Stimuli

Stimulus pool

The total stimulus pool of the study consisted of high-resolution color photographs of 86 food stimuli (43 high-caloric food stimuli, 43 low-caloric food stimuli). To reduce potential biases of a specific picture of a food, each food was portrayed in two versions, yielding a total stimulus set of 172 pictures. Images were obtained from the internet and from the database of the Eating Behavior Laboratory, Salzburg University (Blechert, Lender, Polk, Busch, & Ohla, 2019; Blechert, Meule, Busch, & Ohla, 2014).

Stimulus selection

A subset of images from the stimulus pool was presented to each participant. An online questionnaire was used to tailor the stimuli to the food preferences of the participant. In this questionnaire, the participant was asked to select her three most and three least preferred high-caloric and low-caloric foods. According to the selection of the participant, the food stimuli were grouped into four categories: high-caloric palatable food (HC+), high-caloric unpalatable food (HC-), low-caloric palatable food (LC+), and low-caloric unpalatable food (LC-). In this way, 24 different food images, depicting 12 different foods, were selected and presented to the participant during a one-back task.

Stimulus ratings

In the online questionnaire, the participant was asked to rate the palatability (1: absolutely not tasty; 10: extremely tasty) and the estimated caloric content (1: very few kilocalories; 10: very many kilocalories) separately for high-caloric and low-caloric food stimuli.

Stimulus presentation

During the one-back task, the food images were displayed centrally on a light grey background (RGB: 191 191 191) with a size of approximately twelve degrees of visual angle. During rest periods, a black (RGB: 32 32 32) fixation cross (presented in font size: 32) was presented centrally.

Experimental paradigm

Attentional focus manipulation

Attentional focus was induced using a one-back task while the participant was viewing food pictures in the scanner (see Figure 1). In this task, food pictures were presented in quick succession and the participant had to compare the currently presented food stimulus with the previously presented one, with focus on a certain aspect of the food stimuli. Stimuli were presented in a blocked fashion, and each block contained stimuli from one of the four categories (HC+, HC-, LC+, LC-). So, in the one-back task, stimuli were compared within category. In this way, three attentional foci were induced: a hedonic focus, a health focus, and a neutral focus. A hedonic attentional focus was induced by having the participant focus on the palatability of food stimuli, using the question: “Is the current food item less or more tasty than the previous one?”. A health attentional focus was induced by having participants compare the food stimuli on calorie content, using the question: “Does the current food item contain fewer or more calories than the previous one?”. A neutral attentional focus was induced by having the participant compare the presented food stimuli on color, using the question: “Does the current food item contain fewer or more colors than the previous one?”. Each of the attentional foci (hedonic focus, health focus, neutral focus) was combined with each of the four categories (HC+, HC-, LC+, LC-), yielding twelve conditions.

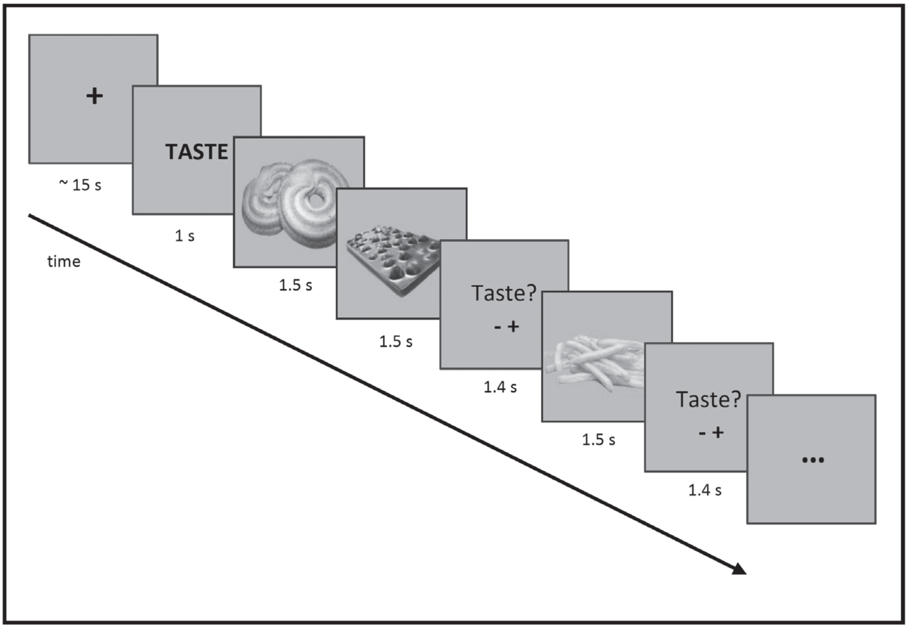

Figure 1: Schematic depiction of the one-back task used to manipulate attentional focus: here an excerpt of a block with hedonic attentional focus with high-caloric food stimuli is shown; in the hedonic focus “taste”, in the health focus “calories”, and in the neutral focus “color” was displayed at the start of the block; in each block one category of food stimuli was presented (either HC+, HC-, LC+, or LC-): in each block 6 food stimuli were display and each block had a duration of 16 s

Task procedure

First, an anatomical scan was conducted. Thereafter, four functional runs were performed.[1] In each functional run, each condition was repeated twice in randomized, mirrored order (e.g., 8 6 10 1 3 7 5 4 9 12 2 11 11 2 12 9 4 5 7 3 1 10 6 8), yielding twenty-four blocks per run. In this way, each condition was presented 8 times during the study. In each block, 6 food pictures (2 versions of 3 different foods) were presented for 1.5 seconds each, and each followed by a response interval of 1.4 seconds[2]. During the response interval, a minus and a plus sign were presented on the screen, together with a repetition of the current attentional focus. That is, either the word ‘taste’, ‘calories’, or ‘color’ was displayed. The response was given on a button box, and the participant was instructed to press one button with her index finger to indicate ‘less’, and to press another button with her middle finger to indicate ‘more’. Response latencies were recorded as measure of task difficulty. Each block lasted 16 s and was preceded by an attentional focus instruction text (black font color (RGB: 32 32 32), font size 32) stating either ‘Taste’, ‘Calories’ or ‘Color’, which was presented for 1 s. Each block was preceded by a rest interval during which a fixation cross was presented. The duration of the rest interval was jittered around a mean of 15 s. The task was administered using Presentation software (Version 18.1, Neurobehavioral Systems, Inc., Berkeley, CA, www.neurobs.com).

Visual similarity rating

After scanning, the participant was asked to rate the similarity in shape and color of all possible unique pairs of the twelve foods presented during scanning on a five-point scale (1: not similar at all, 5: highly similar). To do this, the stimuli were presented next to each other on a black background and with a rating scale underneath. The participant was instructed to give her answer by pressing the corresponding button (1 – 5) on the keyboard. Shape and color similarity ratings were done in separate blocks. Only one image version of each food was used during this task, and it was determined

1 For two participants only three functional runs were performed due to technical problems.

2 With exception of the first image of each block.

randomly which image version was used. This yielded 66 possible pairings of food stimuli. The aim of the visual similarity rating was to check if food stimuli from the same category were not more perceptually similar than food stimuli belonging to different categories based on calorie content or palatability. This was done to be able to exclude the possibility that differences in brain activation can be explained by perceptual properties of the stimuli.

Scanning parameters

The scanning session took place at Scannexus (Maastricht, the Netherlands). A 3 Tesla MRI scanner (Magnetom Prisma Fit, Siemens Medical Systems) with a 64-channel head/neck coil was used to collect the data. Foam cushions were placed at the side of the participant's head to stabilize it. Images were projected to a screen which was viewed through a mirror attached to the head coil. A high-resolution three-dimensional T1-weighted anatomical scan was obtained (MPRAGE pulse sequence, TR = 2250 ms, TE = 2.21 ms, flip angle = 9°, FOV = 256 x 256 mm, voxel size 1 x 1 x 1 mm). T2*-weighted functional images were gathered in an axial interleaved fashion using multiband gradient echo-planar imaging (Feinberg et al., 2010; Moeller et al., 2010; Setsompop et al., 2012) (TR = 2000 ms, TE = 30 ms, flip angle = 77°, FOV = 208 x 208 mm, voxel size of 2 x 2 x 2 mm, 62 slices with multiband factor 2 and GRAPPA2). Slices were acquired with a tilt of approximately fifteen degrees in the sagittal plane to reduce signal dropout near the orbitofrontal cortex. Slices covered the whole brain. During each functional run 386 volumes were collected.

Procedure

Upon initial contact, the participant was screened for neurological illnesses and MRI safety issues. Approximately a week before participation, the participant filled in the online questionnaire to assess dietary restraint and food preferences. On the testing day, the participant was welcomed at the scanning facility. At the beginning of the experiment, the participant was informed about the scanning procedure, signed the informed consent form, filled out a hunger rating questionnaire, and received an offline training of the experimental task, which took approximately thirty minutes. Thereafter, height and weight of the participant were measured. Then, the participant entered the scanner for the anatomical scan and four functional runs. The scanning session took approximately 1.5 hours. Afterwards, the visual similarity rating task was performed outside of the scanner. This task took approximately fifteen minutes. At the end of the experiment, the participant was thanked and received compensation.

Analyses

Analysis response latencies

Response latencies from the one-back task, performed during the functional runs, were analyzed to assess whether the different versions of the task (i.e., different attentional foci) differed in difficulty. First, trials without response (6.55%) and trials with response latency of more than three standard deviations from the mean across participants (i.e., too slow trials (0%) and too fast trials (1.23%)) were excluded from the response latency analysis. Average response latency per block type was calculated and analyzed in a 2 (calorie content: high vs. low) x 2 (palatability: palatable vs. unpalatable) x 3 (attentional focus: hedonic vs. health vs. neutral) repeated measures ANOVA.

Visual similarity rating analysis

Visual similarity ratings were analyzed to assess if within-category perceptual similarity was greater than between-category perceptual similarity. To do so, pairs of food stimuli were categorized once according to calorie content and once according to palatability, each time collapsing over the other factor. Similarity for same category pairs (e.g., high-caloric – high-caloric or palatable – palatable) and different category pairs (e.g., high-caloric – low-caloric or palatable – unpalatable) was calculated. Average similarity of same vs. different category pairs were compared using paired-samples *t*-tests. This procedure was done separately for shape and color ratings.

fMRI analysis

The analysis of the fMRI data was performed with SPM12 (Statistical Parametric Mapping, London, UK), using MATLAB version 9.6.0.1072779 (R2019a).

Pre-processing

Before performing analyses, the data were preprocessed. Firstly, slice-timing correction was applied, with middle slice as reference. Next, small head movements were corrected by three-dimensional motion correction using second degree B-spline interpolation. Translation (x, y, and z direction) and rotation (roll, pitch, and yaw) parameters were estimated, and volumes were aligned to the mean for each functional run. Movement was considered excessive if it exceeded 3 mm in translation or 3 degrees in rotation in any direction. Runs with excessive movements were excluded from further analysis (resulting in the exclusion of 5 runs across 5 subjects). If two or more runs of a participant contained excessive movement, all data of the participant was excluded from the analysis, resulting in 8 participant exclusions. Following motion correction, co-registration between anatomical and functional data was performed by warping the anatomical scan to the mean functional data space, to align anatomical and functional images. A unified segmentation procedure was performed on the images to derive deformation fields. These deformation fields were used to perform spatial normalization to transform the images to MNI space (Montreal Neurological Institute, Montreal, Canada). The functional data were temporally filtered using a high-pass filter with a cut-off period of 128 s (= 0.008 Hz) to remove low-frequency drifts. Finally, spatial smoothing was performed with Gaussian Kernel of 6 mm full width half-maximum (FWHM).

Univariate analysis

Frequentist analysis

During first-level analysis, a general linear model (GLM) was estimated for each participant. In the GLM, a predictor was defined for each condition, yielding 12 predictors of interest per run. To obtain the time-courses for the predictors of interest, a box-car shaped function was convolved with a canonical two-gamma hemodynamic response function (HRF). The six motion parameters that were estimated during pre-processing were added as nuisance regressors. This was done for each of the four runs separately. For each run, a mean intensity regressor was added to the GLM as predictor of no interest. Contrasts for the main effect of calorie content and the main effect of palatability were computed from the GLM for each participant. To test the main effect of attentional focus, the calorie content by attentional focus interaction, and the palatability by attentional focus interaction, two *t*-contrast vectors were defined for each participant, covering further vectors needed to test the effects in second-level analysis by linear combination.

During second level analysis, a whole-brain random effects analysis was performed. Contrast images from the first-level analysis were used as input and dietary restraint was entered as covariate in all second-level analyses, to test if dietary restraint moderated any of the effects of interest. *t*-contrasts were used to test the main effect of calorie content and the main effect of palatability at group-level. *F*-contrasts, which used two *t*-contrast vectors per participant as input, were used to test the main effect of attentional focus, the calorie-content-by-attentional focus interaction, and the palatability-by-attentional focus interaction at group-level. Resulting statistical maps were thresholded at an alpha of 0.05 using voxel-level family-wise error (FWE) correction to adjust for multiple testing (Eklund, Nichols, & Knutsson, 2016; Han & Glenn, 2018). To also consider the risk of false negatives, the analyses were repeated with a more lenient cluster-level FWE-correction, at a cluster-defining threshold of $p < .001$, and cluster-extent threshold determined per analysis in SPM12. Follow-up analyses were performed for the significant main effect of attentional focus. To do this, functional regions of interest (fROIS) were created from significantly activated clusters using the MarsBar toolbox (http://marsbar.sourceforge.net/) in SPM. From these fROIS, average beta values were extracted for each attentional focus. Differences in beta values between attentional foci (i.e., hedonic vs. health, hedonic vs. neutral, health vs. neutral) were analyzed using paired samples *t*-tests in Microsoft Excel (2016).

Bayesian analysis

Bayesian second level analysis was performed using a MATLAB toolbox (Krekelberg, 2020; https://doi.org/10.5281/zenodo.4394423). The analysis was based on the GLM estimates per participant that were used in the frequentist analysis. A Bayesian one-sample *t*-test was performed to compare the plausibility of the alternative hypothesis and the null hypothesis regarding the effects of calorie content and palatability. For palatability, the alternative hypothesis states that the level of brain activity will be increased for palatable food compared unpalatable food. The null hypothesis states that the level of brain activity will not differ between palatable and unpalatable food. For calorie content, the alternative hypothesis states that level of brain activity will be increased for high-caloric food compared to low-caloric food. The null hypothesis states that the level of brain activity will not differ between high-caloric and low-caloric food. To assess the meaning of the observed distribution of Bayes Factors, a Bayesian *t*-test was also performed on simulated null hypothesis data. We used the prior specification for the null and alternative hypothesis as suggested by Rouder, Morey, Speckman, and Province (2012) and implemented by Krekelberg (2020), with a Cauchy prior on the mean (under H1) and a Jeffrey's uninformative prior on the variance of the population (both under H0 and H1).

To test if effects of palatability, calorie content, or attentional focus depends on dietary restraint, a Bayesian Analysis of Covariance (ANCOVA) was performed. Due to high computational requirements, the analysis was performed only in four regions of interest (ROIs): left inferior frontal gyrus, left middle insular cortex, left posterior fusiform gyrus, and right posterior fusiform gyrus. The ROIs were based on results of a meta-analysis (van der Laan et al., 2011) and were created as spheres around the center coordinates in SPM12 (see Table 1). For each ROI, a model containing only main effects of factors palatability, calorie content, attentional focus, and dietary restraint was compared to a model containing those main effects and an interaction between either palatability, calorie content, or attentional focus and dietary restraint. So, a separate model for each interaction was computed. Next, the distribution of Bayes factors was examined to assess the plausibility of an interaction with dietary restraint. In these analyses, we also used the priors proposed by Rouder et al. (2012), with a non-informative prior on mean and residual variance, and a G-prior with independent Cauchy distributions.

Table 1: ROIs used in Bayesian analysis to assess the interaction between calorie content, palatability, attentional focus and dietary restraint respectively

ROI	Centre coordinates	Size
Left inferior frontal gyrus	-26 32 -14	8.35
Left middle insular cortex	-26 32 -14	6.71
Left posterior fusiform gyrus	-30 -56 -10	9.00
Right posterior fusiform gyrus	38 -74 -14	8.52

Multivariate analysis

Whereas univariate analyses of fMRI data are mainly informative of the *involvement* of certain brain regions in certain tasks, MVPA of fMRI data decodes *representational content* in the brain (Haxby et al., 2001; Norman, Polyn, Detre, & Haxby, 2006). MVPA was conducted to test if calorie content and palatability of food stimuli can be decoded above chance from multi-voxel activity patterns. Decoding analysis of calorie content and palatability were carried out across attentional foci as well as for each attentional focus separately. It was tested if decoding accuracy differed significantly between attentional foci.

MVPA was performed using the CoSMoMVPA toolbox (Oosterhof, Connolly, & Haxby, 2016) in MATLAB. Functional images that were pre-processed as described earlier except for spatial smoothing were used input for the analysis (Mur, Bandettini, & Kriegeskorte, 2009). The design matrix was set in the same way as for the univariate analysis except that it contained one predictor for each block, yielding 24 predictors per run. This was done to have more training examples as input for the classification procedure. Whole-brain classification was performed using a 100-voxel spherical searchlight (Kriegeskorte, Goebel, & Bandettini, 2006) with a linear support-vector machine as classification algorithm.

Decoding accuracy was computed for each participant individually. For decoding calorie content, data were partitioned into high-calorie blocks and low-calorie blocks, thereby collapsing across palatability. For decoding palatability, data were partitioned into palatable and unpalatable blocks, thereby collapsing across calorie content. This was done for each attentional focus individually and across attentional foci. Data of three runs were used to train the classifier while the data of the remaining run were used for testing classification accuracy[3]. This procedure was repeated four times, following a leave-one-run-out cross validation procedure.

Afterwards, decoding accuracies were analyzed across participants. Therefore, subject-level classification accuracy maps were spatially smoothed with a Gaussian kernel of 6 mm FWHM before group analysis. Group analysis included only voxels that showed 90 % overlap across participants to exclude voxels with poor group overlap. Mean decoding accuracies for decoding calorie content and palatability were non-parametrically tested, using Wilcoxon signed-rank tests, against chance level (0.5) for within and across attentional focus decoding, and against zero for testing differences in decoding between attentional foci. All results were FDR-corrected on voxel-level (Benjamini & Hochberg, 1995; Genovese, Lazar, & Nichols, 2002).

Results

Fifty-two normal weight women (BMI: *M* = 22.15, *SD* = 1.91, range: 18.08 – 25.94) with varying levels of dietary restraint (*M* = 13.92, *SD* = 5.00, range: 4 - 26) participated in the current fMRI study. Dietary restraint was measured with the revised restraint scale (Herman & Polivy, 1980). The food images presented during scanning were individually tailored to the taste-preferences of each participant, yielding the following four food categories: high-caloric palatable food (HC+), high-caloric unpalatable food (HC-), low-caloric palatable food (LC+), and low-caloric unpalatable food (LC-). The attentional focus of the participant was manipulated with a one-back task, in which successive food stimuli were compared on palatability to induce a hedonic attentional focus, on calorie content to induce a health attentional focus, or on color to induce a neutral attentional focus. The food categories were combined with the attentional foci in a blocked design, yielding twelve block types. Perceived similarity in color and shape of the presented food stimuli was rated after the scan session (see Methods for a full description).

3 For five participants only data of three functional runs were available (due to technical problems during scanning or excessive head movement during a run). For those participants, data of two runs were used to train the classifier.

Manipulation Checks

Stimulus ratings

To check if the individually tailored food stimuli were perceived as intended, two separate 2 (calorie content: high vs. low) x 2 (palatability: palatable vs. unpalatable) repeated measures ANOVAs were performed, on palatability ratings and on calorie content ratings.

Palatability ratings

There was no significant main effect of calorie content on palatability ratings ($F_{1,51} = 0.005$, $p = .942$, $\eta_p^2 < 0.001$). As expected, palatable food was rated as more palatable than unpalatable food, as evidenced by a significant main effect of palatability ($F_{1,51} = 384.991$, $p < .001$, $\eta_p^2 = 0.881$). Also, there was a significant interaction between calorie content and palatability on palatability ratings ($F_{1,51} = 5.703$, $p = .021$, $\eta_p^2 = 0.099$), indicating that the difference between palatable and unpalatable high-caloric food was slightly larger than for low-caloric food. See Table 2 for relevant means and SDs.

Caloric content ratings

As expected, the caloric content of high-caloric food was estimated to be higher than that of low-caloric food, as evidenced by a significant main effect of calorie content ($F_{1,51} = 329.860$, $p < .001$, $\eta_p^2 = 0.864$). In addition, palatable food was estimated to be higher in calories than was unpalatable food, as evidenced by a significant main effect of palatability ($F_{1,51} = 71.499$, $p < .001$, $\eta_p^2 = 0.579$). The calorie content x palatability interaction was significant as well, ($F_{1,51} = 14.306$, $p < .001$, $\eta_p^2 = 0.216$), suggesting that the difference in calorie content ratings between palatable and unpalatable food was larger for high-caloric than for low-caloric food. See Table 2 for relevant means and SDs.

Taken together, these analyses indicate that individual tailoring of food stimuli was successful, and that the four stimulus categories were rated as intended (see Table 2).

Table 2: Overview of means and standard deviations of palatability and calorie content ratings of the individually tailored food stimuli

	HC+		HC-		LC+		LC-	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Palatability rating	9.19	1.34	2.71	1.34	8.96	1.32	2.95	1.66
Calorie content rating	8.72	0.95	6.90	1.37	3.85	1.66	3.29	1.48

Hunger rating

We attempted to standardize hunger level by instructing participants to refrain from eating and drinking anything except water for two hours before the experiment. To check if this instruction was successful, we assessed time passed since the last eating moment and self-reported hunger level by means of a questionnaire at the beginning of the experiment. The time passed since the last eating moment was on average slightly longer than instructed (*M* = 151.06 minutes, *SD* = 39.25 minutes). On average, participants reported moderate hunger levels (*M* = 41.33, *SD* = 26.12). Hunger level was not significantly correlated with dietary restraint (r_{50} = -0.167, *p* = .237).

Behavioral data

Response latencies

Response latencies were recorded during the one-back task as measure of task difficulty. Mean reaction times per block type were analyzed in a 2 (calorie content: high vs. low) x 2 (palatability: palatable vs. unpalatable) x 3 (attentional focus: hedonic vs. health vs. neutral) repeated measures ANOVA. There was a significant main effect of attentional focus ($F_{1.960,99.979}$ = 6.419, *p* = .003, η_p^2 = 0.112). Participants responded slightly faster in the neutral attentional focus condition (color comparison; *M* = 442.167, *SD* = 85.463) than in the hedonic (*M* = 454.686, *SD* = 81.837; t_{51} = 2.927, *p* = .005) or health condition (*M* = 457.201, *SD* = 81.228; t_{51} = 3.134, *p* = .003), whereas there was no significant difference in response latency between the hedonic and health condition (t_{51} = 0.572, *p* = .570). This could indicate that the neutral attentional focus condition was slightly easier than the other two conditions. None of the other main or interaction effects reached significance, all *F* < 2.844, all *p* > 0.067.

Visual similarity rating

To be able to exclude the possibility that differences in brain response to different food types could be explained by perceptual properties of the stimuli, we tested whether food stimuli from the same category were more perceptually similar than food stimuli from different categories based on either calorie content or palatability. Food stimuli matching on calorie content (color: M = 2.21, SD = 0.53; shape: M = 1.93, SD = 0.47) were on average more similar in color and shape than food stimuli differing in calorie content (color: M = 1.82, SD = 0.38; shape: M = 1.62, SD = 0.40) (color: t_{51} = 6.04, p < 0.001, d = 0.838; shape: t_{51} = 6.61, p < 0.001, d = 0.917). Food stimuli matching on palatability (color: M = 2.05, SD = 0.39; shape: M = 1.79, SD = 0.42) were on average slightly more similar in color than food stimuli differing in palatability (color: M = 1.95 SD = 0.44; shape: M = 1.74, SD = 0.41) (color: t_{51} = 2.43, p = .019, d = 0.337) but not in shape (shape: t_{51} = 1.67, p = .101, d = 0.232). However, the low mean similarity ratings (range: 1.62 – 2.21 on a scale of 1 (not similar at all) to 5 (highly similar)) showed that stimuli were perceived as rather dissimilar, and differences in observed similarity were numerically small (range: 0.05 – 0.39 on a 5-point scale).

Univariate analysis

Frequentist analysis

In a whole-brain univariate analysis with voxel-level FWE correction, the main effect of calorie content, the main effect of palatability, the main effect of attentional focus, the calorie content x attentional focus interaction, and the palatability x attentional focus interaction were examined. The palatability x attentional focus interaction and the calorie content x attentional focus interaction did not result in significant clusters of brain activity. The main effect of calorie content resulted in four clusters (inferior temporal gyrus and parahippocampal gyrus), with more activity in response to high- than to low-caloric foods (see Table 3). No clusters with a significantly stronger response to low-caloric than to high-caloric food images were found. No significant activation was found for the main effect of palatability, meaning that no regions could be detected that responded significantly stronger to palatable food than to unpalatable food, or the other way around. The main effect of attentional focus yielded 28 significantly activated clusters (see Table 4 & Figure 2), which among others were located in several regions of the mesocorticolimbic system. Several regions, which were mostly located in the prefrontal cortex, responded significantly stronger in the hedonic attentional focus than in the health or neutral attentional focus, while a few regions responded significantly stronger in the neutral attentional focus than in the health or hedonic attentional focus. All observed patterns of effects can be found in Table 4.

Repeating the analysis with a more lenient cluster-level FWE-correction at cluster-defining threshold of $p < .001$, and cluster-extent threshold determined per analysis in SPM12, we observed four clusters with a significantly higher activity level for high-caloric food than for low-caloric food (cluster-extent threshold: 240 voxels), located in inferior/medial frontal gyrus, parahippocampal gyrus, and inferior/middle temporal gyrus. In addition, we observed 2 clusters with a significantly higher activity level for low-caloric food than for high-caloric food (cluster-extent threshold: 232 voxels), located in cuneus, lingual gyrus, and middle occipital gyrus. However, with this more lenient multiple comparison correction approach, we did not find any significant effects of palatability or dietary restraint on brain responses to food.

Effect of dietary restraint

In all analyses, dietary restraint was added as covariate. No significant effects of dietary restraint were observed in any of the analyses.

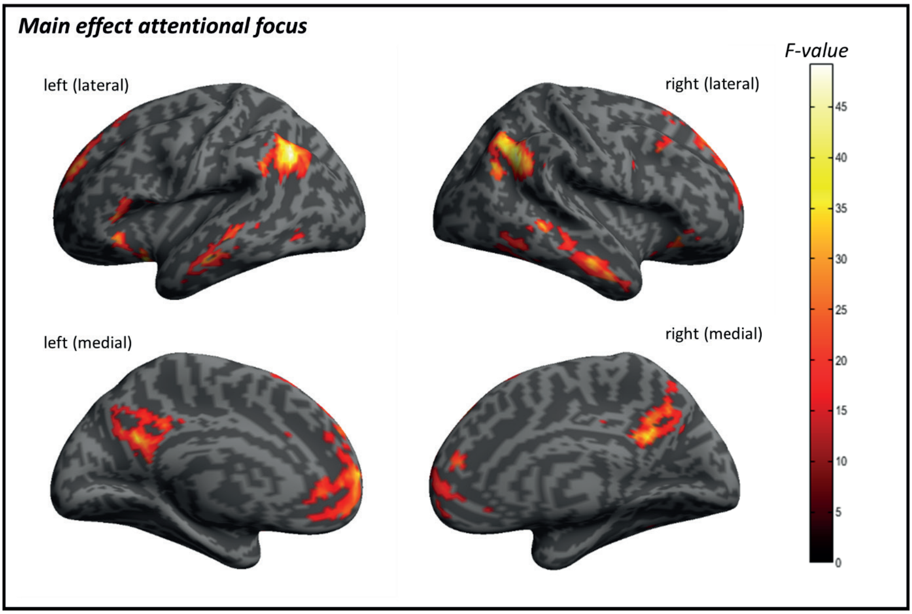

Figure 2: Significant clusters from univariate analysis (p < 0.05, FWE corrected, displayed are clusters > 10 voxels) for the main effect of attentional focus; visualizations were created in SPM12

Table 3: Significant clusters from univariate analysis contrasting high-caloric > low caloric food (*p* < 0.05, FWE corrected voxel level); clusters in brain regions related to food decision making in previous literature are printed in black font color, clusters in brain regions not related to food decision making in previous literature are printed in grey font color

Cluster	Region	H	Cluster size	Peak coordinates (MNI)	Peak F/t value	Cluster p-value
Contrast: high-caloric > low-caloric						
2	Inferior Frontal Gyrus	L	9	-24 30 -12	5.96	.004
1	Parahippocampal Gyrus	L	4	-22 -34 -14	5.61	.011
3	Parahippocampal Gyrus	L	1	-24 -28 -12	6.02	.027
4	Temporal Lobe	L	2	-48 -52 -6	5.55	.019

Table 4: Significant clusters from univariate analysis of the main effect of attentional focus ($p < 0.05$, FWE corrected on voxel-level); significant clusters are grouped according to beta value pattern; clusters in brain regions related to food decision making in previous literature are printed in black font color, clusters in brain regions not related to food decision making in previous literature are printed in grey font color

Cluster	Region	H	Cluster size	Peak coordinates (MNI)	Peak *F*-value	Cluster *p*-value	Beta value			*p*-value		
							hedonic	health	neutral	hedonic vs health	hedonic vs neutral	health vs neutral
Contrast: Main effect attentional focus												
beta value pattern: hedonic > health > neutral												
18	Precuneus/ Cingulate gyrus	B	1580	6 -50 32	44.57	< .001	0.04	-1.44	-3.03	< .001	< .001	< .001
26	Middle Frontal Gyrus	L	1	-32 24 34	16.16	.029	2.42	1.84	1.11	.008	< .001	< .001
1	Cerebellum Posterior Lobe	R	489	22 -88 -42	29.37	< .001	-0.12	-2.14	-3.30	< .001	< .001	.011
2	Cerebellum Posterior Lobe	R	139	46 -70 -38	26.95	< .001	3.53	1.86	0.53	< .001	< .001	.001
3	Cerebellum Posterior Lobe	R	14	6 -52 -40	19.05	.002	0.62	-0.01	-0.65	.002	< .001	.005
5	Cerebellum Posterior Lobe	L	54	-48 -66 -38	22.23	< .001	2.42	0.85	-0.28	< .001	< .001	.013
25	Cingulate Gyrus	L	6	-2 -14 36	18.28	.008	0.72	-1.22	-2.21	.036	< .001	.001
beta value pattern: hedonic > (health = neutral)												
8	Frontal Lobe: Superior Frontal Gyrus/ Medial Frontal Gyrus/ Cingulate Gyrus	B	4443	-2 62 10	41.52	< .001	-2.74	-5.30	-5.83	< .001	< .001	.126
10	Inferior Frontal Gyrus	L	704	-28 14 -18	50.25	.005	2.75	0.94	0.36	< .001	< .001	.057
11	Inferior Frontal Gyrus/ Insula	R	173	44 22 -10	27.97	< .001	0.28	-1.52	-1.80	< .001	< .001	.324
16	Superior Frontal Gyrus/ Inferior Frontal Gyrus	L	2	-22 54 -6	16.59	.021	3.60	1.65	1.11	< .001	< .001	.262
19	Anterior Cingulate	L	5	-4 36 18	18.31	.010	-1.46	-2.46	-2.90	< .001	< .001	.067
21	Anterior Cingulate	L	1	-8 40 18	16.21	.029	-1.42	-2.55	-2.67	< .001	< .001	.636
27	Middle Frontal Gyrus	L	19	-32 30 48	18.85	.001	-1.45	-3.71	-3.74	< .001	< .001	.938
28	Superior Frontal Gyrus/ Middle Frontal Gyrus	L	17	-42 12 52	18.35	.001	6.65	4.00	4.21	< .001	< .001	.672

Cluster	Region	H	Cluster size	Peak coordinates (MNI)	Peak F-value	Cluster p-value	Beta value			p-value		
							hedonic	health	neutral	hedonic vs health	hedonic vs neutral	health vs neutral
4	Cerebellum Posterior Lobe	L	452	-32 -86 -36	30.10	< .001	0.52	-2.96	-3.50	< .001	< .001	.219
6	Middle Temporal Gyrus/ Inferior Temporal Gyrus	R	920	56 0 -32	35.27	< .001	0.66	-1.65	-1.61	< .001	< .001	.905
7	Middle Temporal Gyrus/ Inferior Temporal Gyrus	L	429	-62 -16 -18	32.89	< .001	-0.32	-2.38	-2.46	< .001	< .001	.815
17	Superior Temporal Gyrus/ Middle Temporal Gyrus	L	9	-56 -46 4	18.11	.004	0.62	-1.68	-1.74	< .001	< .001	.889
22	Supramarginal Gyrus/ Inferior Parietal Lobule/ Angular Gyrus/ Superior Temporal Gyrus	R	1155	52 -62 34	49.20	< .001	-0.06	-4.12	-4.39	< .001	< .001	.620
23	Supramarginal Gyrus/ Inferior Parietal Lobule/ Superior Temporal Gyrus/ Middle Temporal Gyrus	L	1085	-50 -64 34	49.27	< .001	2.99	-1.20	-1.68	< .001	< .001	.371
beta value pattern: neutral > (health = hedonic)												
9	Fusiform Gyrus	R	7	30 -40 -18	17.52	.006	4.94	4.83	5.98	.464	< .001	< .001
13	Fusiform Gyrus	R	13	32 -50 -14	20.36	.002	8.49	8.44	9.76	.792	< .001	< .001
20	Inferior Frontal Gyrus	R	2	46 36 16	16.50	.021	4.28	4.27	6.82	.984	< .001	< .001
24	Inferior Frontal Gyrus	R	14	48 4 30	18.30	.002	3.56	3.44	5.33	.634	< .001	< .001
12	Middle Temporal Gyrus/ Inferior Temporal Gyrus	R	211	50 -52 -14	24.97	< .001	7.19	6.93	9.76	.429	< .001	< .001
15	Middle Temporal Gyrus/ Inferior Temporal Gyrus/ Middle Occipital Gyrus	L	53	-46 -64 -6	25.74	< .001	13.58	14.05	16.21	.191	< .001	< .001
beta value pattern: (neutral = health) > hedonic												
14	Lingual Gyrus	L	8	-18 -88 -6	19.15	.005	35.31	37.35	37.55	< .001	< .001	.635

Bayesian analysis

A whole-brain mass-univariate Bayesian *t*-test was used to compare the evidence in favor of an effect of palatability (palatable > unpalatable) against the evidence in favor of no effect of palatability on brain activity level in response to food. Overall, the observed Bayes Factors were small, suggesting evidence for no effect of palatability. Only 4.8 % of voxels showed evidence in favor of an effect of palatability, with 3.58 % of voxels showing anecdotal evidence and 1.22 % of voxels showing moderate evidence (Figure 4; range of $\log_{10}$ of Bayes Factors: -1.67 – 3.13; for reference values see Kass and Raftery (1995)). Because the Bayes Factors were computed independently on each voxel, we observed a distribution of values, which we compared with a distribution of Bayes Factors computed on simulated null data. This comparison suggests that the observed data support the null hypothesis (Figure 4). Overall, the analysis supports the notion that there is no effect of palatability in the univariate results.

Similarly, a whole-brain mass-univariate Bayesian *t*-test was used to compare the evidence in favor of an effect of calorie content (high-calorie > low-calorie) against the evidence in favor of no effect of calorie content on brain activity level in response to food. Most voxels showed no evidence in favor of an effect of calorie content. However, 11.7 % of voxels showed evidence in favor of an effect of calorie content. More specifically, 6.92 % of voxels showed anecdotal evidence for the alternative hypothesis, and 4.77% of voxels showed moderate evidence for the alternative hypothesis (Figure 5; range of $\log_{10}$ of Bayes Factors: -1.77 – 5.28. for reference values see Kass and Raftery (1995)). So, some voxels showed evidence for an increased brain activity level in response to high-caloric than to low-caloric food, whereas most voxels showed no effect of calorie content. Comparing the distribution of Bayes factors on actual data with a distribution of Bayes Factors on simulated null data suggest that the observed data indeed support that some regions showed increased activity for high-caloric compared to low-caloric food (Figure 5), confirming the frequentist univariate results.

A region-of-interest (ROI) analysis was used to check for possible interactions with dietary restraint, using a Bayesian ANOVA. In none of the tested ROIs

(Table 1), evidence in favor of an interaction between dietary restraint and a factor (palatability, calorie content, attentional focus) was observed. Instead, in all regions evidence in favor of the null hypothesis of no interaction was found (Figure 6; for reference values see Kass and Raftery (1995)).

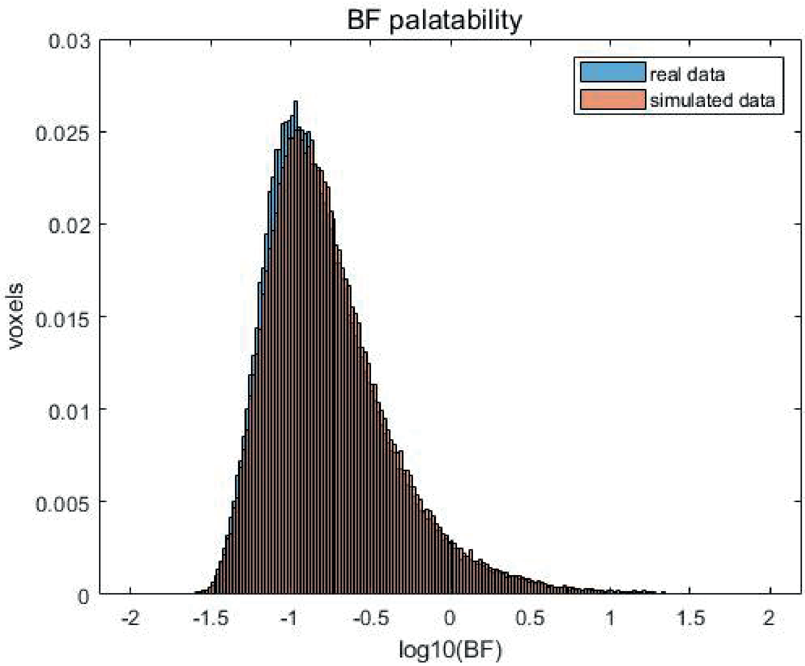

Figure 4: Distribution of log10 of Bayes Factors assessing the contrast palatable > unpalatable for real and simulated data. Both distributions largely overlap and show evidence predominately in favor of the null hypothesis.

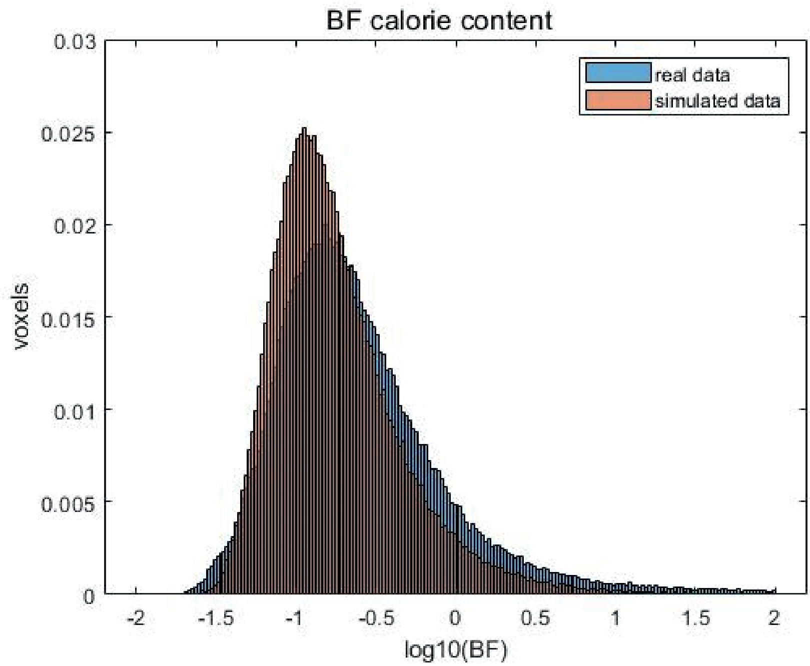

Figure 5: Distribution of $\log_{10}$ of Bayes Factors assessing the contrast high-calorie > low-calorie unpalatable for real and simulated data. Overlap between both distribution is large, and most voxels show evidence in favor of the null hypothesis. However, some voxels show evidence in favor of the alternative hypothesis.

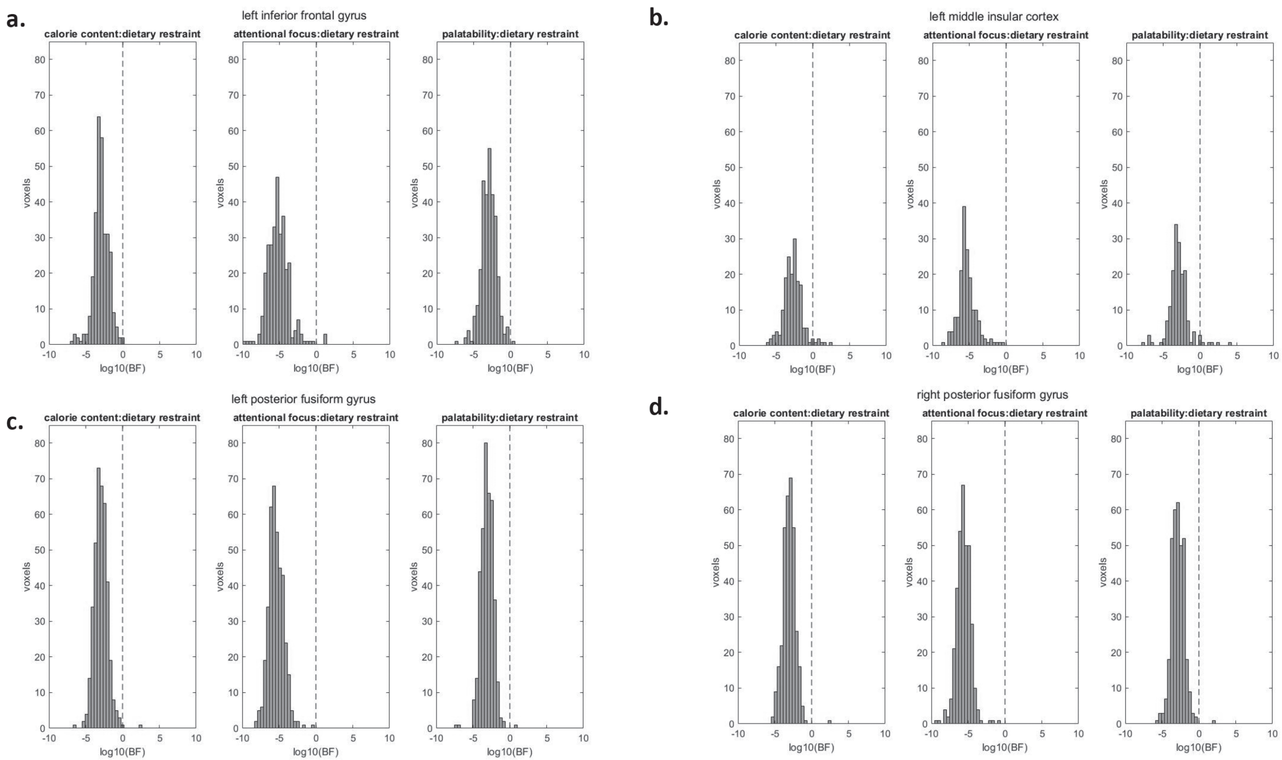

Figure 6: Log_{10} of Bayes factors for the interactions between calorie content, attentional focus, palatability and dietary restraint respectively; a: in left inferior frontal gyrus ROI; b: in left middle insular cortex ROI; c: in left posterior fusiform gyrus ROI; d: in right posterior fusiform gyrus ROI; in all ROIs, most of the observed Bayes factors (log_{10}) are smaller than zero, indicating support for the null hypothesis

Multivariate analysis

We carried out MVPA using a whole-brain searchlight approach (Kriegeskorte et al., 2006) to test if calorie content and palatability of food stimuli could be decoded above chance from multi-voxel activity patterns. This was done across attentional foci (see Figure 3) and for each attention focus separately (see Supplementary Figure 1 & Supplementary Figure 2). We also tested if decoding accuracy differed significantly between attentional foci. All results were FDR-corrected for multiple comparisons on the voxel-level (Benjamini & Hochberg, 1995; Genovese et al., 2002). Palatability and calorie content could be decoded significantly above chance in several regions of the mesocorticolimbic system within each attentional focus and across attentional foci (see Table 5 & 6). We did not find any significant differences in decoding accuracies between attentional foci when decoding palatability or calorie content.

Effect of dietary restraint

For all analyses, correlations between dietary restraint and decoding accuracy were calculated. No significant correlations between dietary restraint and decoding accuracy were observed in any of the analyses.

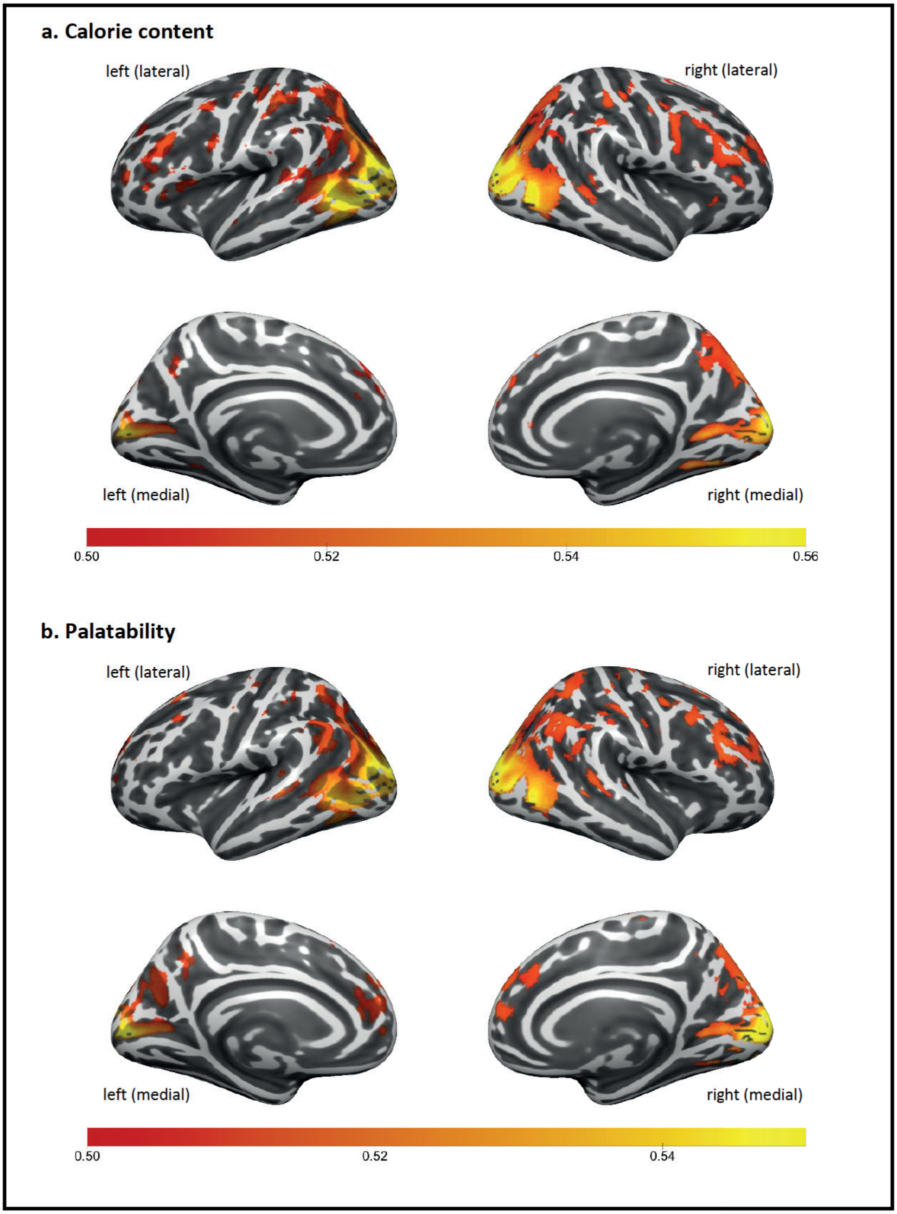

Figure 3: Clusters with decoding accuracy significantly above chance ($p < 0.05$, FDR corrected); a: for decoding calorie content (across attentional foci), b: for decoding palatability (across attentional foci); visualizations were created using FreeSurfer (https://surfer.nmr.mgh.harvard.edu/) and Surf Ice (https://www.nitrc.org/projects/surfice/)

Table 5: Brain regions related to food decision making in previous literature with decoding accuracy significantly above chance (p < 0.05, FDR corrected) for decoding calorie content; H = hemisphere, L = left, R = right, B = Bilateral, MNI = Montreal Neurological Institute

Cluster	Region	H	Cluster size	Peak coordinates (MNI)	Percentage accuracy
Decoding calorie content: across attentional foci					
6	Inferior Frontal Gyrus/ Middle Frontal Gyrus/ Insula/ Precentral Gyrus	R	1293	44 28 20	51.74
7	Middle Fontal Gyrus/ Inferior Frontal Gyrus/ Superior Frontal Gyrus/ Medial Frontal Gyrus/ Precentral Gyrus/ Insula / Anterior Cingulate	L	2235	-36 42 16	51.83
8	Anterior Cingulate	L	14	-8 40 -2	50.86
9	Middle Frontal Gyrus/ Superior Frontal Gyrus	R	69	30 52 2	51.28
10	Anterior Cingulate	R	104	18 38 12	51.37
11	Insula	L	20	-32 8 8	51.02
13	Inferior Frontal Gyrus	L	2	-50 20 10	50.86
15	Superior Frontal Gyrus	R	5	20 60 18	51.01
26	Middle Frontal Gyrus	R	277	34 -2 46	51.37
27	Cingulate Gyrus	L	5	-4 -40 42	50.99
28	Middle Frontal Gyrus	R	39	26 32 44	51.20
29	Medial Frontal Gyrus/ Superior Frontal Gyrus	R	6	8 32 48	51.08
30	Superior Frontal Gyrus	R	63	10 40 50	51.63
33	Superior Frontal Gyrus	R	79	12 24 58	51.34
35	Medial Frontal Gyrus	R	2	16 -16 60	50.79
36	Superior Frontal Gyrus	L	54	-8 8 66	51.05
37	Medial Frontal Gyrus/ Precentral Gyrus	L	55	-8 -22 70	51.18
38	Middle Frontal Gyrus	L	5	-26 -2 62	50.93
39	Superior Frontal Gyrus	L	2	-12 16 64	50.78
41	Middle Frontal Gyrus/ Superior Frontal Gyrus	L	6	-18 -6 68	50.92

Table 6: Brain regions related to food decision making in previous literature with decoding accuracy significantly above chance (p < 0.05, FDR corrected) for decoding palatability; H = hemisphere, L = left, R = right, B = Bilateral, MNI = Montreal Neurological Institute

Cluster	Region	H	Cluster size	Peak coordinates (MNI)	Percentage accuracy
Decoding palatability: across attentional foci					
6	Medial Frontal Gyrus/ Superior Frontal Gyrus/ Anterior Cingulate/ Inferior Frontal Gyrus	B	2987	-28 46 28	51.94
7	Inferior Frontal Gyrus	L	24	-48 18 4	51.04
8	Superior Temporal Gyrus	R	1	52 -42 14	50.55
9	Inferior Frontal Gyrus/ Middle Frontal Gyrus	R	125	50 30 18	51.21
11	Insula	R	13	38 -20 20	50.89
17	Medial Frontal Gyrus/ Superior Frontal Gyrus	R	22	24 36 30	50.94
20	Middle Frontal Gyrus/ Precentral Gyrus/ Inferior Frontal Gyrus	L	322	-38 2 52	51.41
21	Middle Frontal Gyrus/ Superior Frontal Gyrus/ Cingulate Gyrus	R	322	24 22 48	51.70
22	Superior Frontal Gyrus	R	2	24 44 34	50.95
24	Middle Frontal Gyrus	R	12	42 24 40	51.04
30	Middle Frontal Gyrus	L	72	-28 22 48	51.36
31	Postcentral Gyrus/ Inferior Parietal Lobule	R	17	44 -36 52	51.08
32	Postcentral Gyrus/ Precentral Gyrus	L	73	-38 -28 52	51.01
33	Superior Frontal Gyrus	R	3	10 28 52	50.78
34	Superior Frontal Gyrus	L	10	-4 28 52	50.98
35	Medial Frontal Gyrus	L	3	-8 -24 56	50.70
36	Medial Frontal Gyrus	L	2	-8 -20 56	50.82
38	Medial Frontal Gyrus/ Frontal Lobe White Matter	L	7	-18 -14 56	51.03
39	Superior Frontal Gyrus	L	6	-26 12 56	51.01
40	Superior Frontal Gyrus	L	51	-4 24 56	51.10
41	Superior Frontal Gyrus	R	1	16 26 56	50.90
43	Middle Frontal Gyrus	R	84	22 -14 62	51.24
46	Middle Frontal Gyrus/Precentral Gyrus	L	85	-18 -16 62	51.41
48	Middle Frontal Gyrus	L	1	-20 8 64	50.77
51	Superior Frontal Gyrus	R	1	8 -6 68	50.70

Discussion

The current study investigated the effects of attentional focus, food palatability and caloric content on brain responding to visual food stimuli in healthy-weight women, and how these effects are moderated by dietary restraint, using univariate as well as multivariate fMRI analyses. Univariate analyses revealed no brain regions that responded significantly differently to palatable than to unpalatable food stimuli. In addition, only four small clusters, located in the inferior frontal gyrus and parahippocampal gyrus, displayed a significantly higher level of activity for high-caloric than for low-caloric food stimuli. In contrast, a large difference in brain activation levels between attentional foci was detected. A higher level of activity was observed in several regions of the mesocorticolimbic system in the hedonic attentional focus than in health and neutral attentional focus, while the reverse pattern was observed in a few other regions of the mesocorticolimbic system. Multivariate analysis revealed that, by using whole-brain searchlight classification analysis, it was possible to decode palatability and calorie content from several brain regions of the mesocorticolimbic system, across and within attentional foci. Decoding accuracies for palatability and calorie content did not differ significantly between attentional foci. Unexpectedly, none of the effects from univariate or multivariate analysis were significantly moderated by dietary restraint.

A striking finding of the current study is that no differential activity level between palatable and unpalatable food stimuli was detected. Importantly, the lack of differential activation between palatable and unpalatable food stimuli cannot be attributed to a lack of difference in perceived palatability of the presented food stimuli, as the presented food stimuli were individually tailored on palatability and subjective palatability ratings for unpalatable versus palatable food stimuli were highly and significantly different. The lack of differential activation was also observed with a lenient statistical threshold and the absence of an effect of palatability was also supported by Bayesian analysis. This finding contradicts results from several previous studies (LaBar et al., 2001; Martin et al., 2010; Rothemund et al., 2007), which observed widespread activation in the mesocorticolimbic system in response to food stimuli and interpreted this activation as evidence that the presented food stimuli are rewarding.

However, most previous studies did not directly contrast palatable and unpalatable food stimuli, but rather contrasted high-caloric palatable food stimuli against neutral non-food stimuli. In these studies, reward value and salience could therefore not be disentangled, as salience and reward value of each stimulus category coincided. That is, positive/salient stimuli were contrasted against neutral/non-salient stimuli. Reward value is high for very positive stimuli and low for very negative stimuli, whereas salience is high for both very positive and very negative stimuli (Kahnt, 2018; Kahnt & Tobler, 2017). Therefore, it is important to include negative stimuli to truly understand the meaning of brain activation in the mesocorticolimbic system. When contrasting very palatable and very unpalatable stimuli, salience is kept constant across these stimulus categories, enabling the researcher to study the pure effect of stimulus valence.

Interestingly, the current results fit with the results from a recent study (Chikazoe et al., 2014), which also showed that positive and negative valence could not be distinguished in univariate fMRI analyses. Furthermore, the current results are in line with the results from Franssen et al. (2020), who used stimuli that were individually tailored on palatability and contrasted palatable and unpalatable high-caloric food stimuli. Also in this study, no differential level of activation between palatable and unpalatable food stimuli was observed. The current findings extend the findings of Franssen et al. (2020) by adding low-caloric food stimuli and by testing the effect in healthy-weight participants.

Similarly, very little significant differential brain activity was observed between high-caloric and low-caloric food stimuli in univariate analysis. Higher brain responding to high-caloric food stimuli compared to low-caloric food stimuli was observed in only four small clusters (max. cluster size < 10 voxels) located in the inferior frontal gyrus and parahippocampal gyrus. Notably, the small amount of significant differential activation between high- and low-caloric food stimuli cannot be attributed to a lack of perceived difference in calorie content of the presented food stimuli, as calorie content ratings confirmed that high-caloric and low-caloric items were perceived as highly and significantly different in calorie content. Using a more lenient multiple comparison correction yielded slightly more differences in brain activity level (e.g., located in inferior/medial frontal gyrus, parahippocampal gyrus, and inferior/middle temporal gyrus) between high-caloric and low-caloric food, and Bayesian analysis detected some voxels that show an effect of calorie content on brain activity level. However, most of the regions showing differential activity for high versus low caloric food stimuli have not been associated with food reward processing in previous studies. The inferior frontal gyrus has been associated with control processes in food perception (Giuliani, Merchant, Cosme, & Berkman, 2018). Overall, this result is not congruent with some previous studies that reported higher brain activity in several regions of the mesocorticolimbic system, like OFC and insula (Frank et al., 2010; Killgore et al., 2003). In contrast to those studies, which observed differential activation in regions of the mesocorticomlimbic system, the current study employed a much larger sample size and applied a stringent multiple comparison correction. However, the current results fit with another previous study, which did not find differential activation between high- and low-caloric food stimuli (Siep et al., 2009).

Compellingly, the current study found that brain activity depended on attentional focus. The main effect of attentional focus was mainly driven by increased activity levels in the hedonic attentional focus compared to the health or neutral attentional focus. In several regions belonging to the mesocorticolimbic system, like the cingulate gyrus, middle frontal gyrus, and superior frontal gyrus, brain responding to food stimuli was stronger in the hedonic attentional focus than in the neutral or health attentional focus. In a few regions, like the fusiform gyrus, brain activity was stronger in the neutral attentional focus than in the hedonic or health attentional focus. No regions were detected in which the level of activity was strongest in the health attentional focus. It is unlikely that the observed differences between attentional foci resulted from differences in task difficulty (assessed by response latency), as there were no differences in task difficulty between the hedonic and health attentional focus, but there were significant differences in brain activity between these foci. Moreover, differences in task difficulty between the neutral focus and the other two attentional foci were small.

The overall higher level of activity in response to food stimuli in the hedonic attentional focus points towards a higher motivational salience of food or increased reward sensitivity elicited by focusing on hedonic properties of food compared to non-indulgent properties of food, like calorie content or color. In addition, we observed no significant differences in brain activity level between palatable and unpalatable food and almost no significant differences between high-caloric and low-caloric food. Taken together, this combination of findings suggests that the activity level in the mesocorticolimbic system reflects the salience of stimuli or reward sensitivity rather than reward value. That is, if level of brain activity reflected reward value (either defined as palatability or as caloric value), then a significant difference in brain activity between these food categories should have been observed. The results are in line with theory and studies that suggest that both positive and negative stimuli are more salient than neutral stimuli (Kahnt, 2018; Kahnt, Park, Haynes, & Tobler, 2014; Kahnt & Tobler, 2017).

The findings are in line with previous research showing that attentional focus influences brain responding to food stimuli (Bhanji & Beer, 2012; Frankort et al., 2012; Franssen et al., 2020; Hare et al., 2011; Hege et al., 2018; Siep et al., 2012). Especially, the current findings provide a replication of the results of Franssen et al. (2020), with both studies showing that specifically a hedonic attentional focus leads to an increased level of activation in the mesocorticolimbic system. The current study extended the results of Franssen et al. (2020) by adding a health attentional focus. The findings on the effect of a health attentional focus differ from previous studies that found strong effects of an attentional focus on health (Bhanji & Beer, 2012; Hare et al., 2011), but this might be explained by differing conceptualization of the health attentional focus and differing analysis approaches. In general, the significant main effect of attentional focus shows that the brain response to food stimuli depends on the attentional focus of a person, and that brain responses to food stimuli are influenced by cognitive states rather than being automatic reactions that are always the same.

The current findings underline the importance of having a clear mental task when investigating brain responses to food stimuli. It seems that attentional focus can only be manipulated successfully with tasks that meet certain characteristics. That is, like the current study, studies that were successful in detecting effects of attentional focus (Bhanji & Beer, 2012; Franssen et al., 2020; Hare, Malmaud, & Rangel, 2011; van Rijn, de Graaf, & Smeets, 2018) used a manipulation of attentional focus that was centrally embedded in the experimental task. Also, the use of cognitive strategies to manipulate the focus on food stimuli appears to be effective (Miedl, Blechert, Meule, Richard, & Wilhelm, 2018; Siep et al., 2012). It seems crucial that the cognitive strategies are emphasized throughout the task with frequent repetition of instructions. In contrast, more task-independent manipulations of attentional focus, like presenting participants with video messages about attentional focus, appear to be ineffective (Franssen et al., submitted; Kochs et al., in preparation). Possibly, messages that only frame the experimental tasks are not sufficiently important to task performance, and participants might forget about them quickly in an artificial laboratory environment. So, the nature of the experimental task is a crucial factor in research on the effects of attentional focus in brain responses to food.

Multivariate analysis showed that it was possible to decode food palatability and calorie content from numerous brain regions, among which several regions of the mesocorticolimbic system. It is unlikely that decoding was driven by visual properties of stimuli, as stimuli were individualized, were perceived as rather dissimilar, and differences in perceptual similarity between categories were small. The current findings parallel the findings of Franssen et al. (2020), who observed significant decoding of food palatability in a multitude of brain regions, which largely overlapped with the regions observed in the current study. Similarly, the current findings are in line with the observations that information about valence and food value could only be revealed by multivariate analysis techniques (Chikazoe et al., 2014; Suzuki et al., 2017).

Decoding of palatability and calorie content was possible across and within attentional foci, and there were no significant differences in decoding accuracy for palatability or calorie content between attentional foci. This finding differs from the results of Franssen et al. (2020) who observed brain regions in which palatability could be decoded significantly better in the hedonic attentional focus than in the neutral attentional focus. Overall, the current results suggest that food characteristics, like palatability and calorie content, are barely reflected in the level of brain activation, while distributed patterns across voxels contain information about these food characteristics, as revealed by multivariate analysis techniques.

Interestingly, no significant moderation of brain activity related to palatability or calorie content by dietary restraint was detected, suggesting that palatable or high-caloric food is not generally more salient or represented differently in healthy-weight people scoring high on dietary restraint. This lack of findings cannot be attributed to a lack of variation in dietary restraint scores, as the measured range of dietary restraint scores was large. Also, Bayesian analysis results indicate the absence of any interaction with dietary restraint. The current findings are not in line with findings of several previous studies (Born et al., 2011; Coletta et al., 2009; Demos et al., 2011; Ely et al., 2014; Hollmann et al., 2012; Wood et al., 2016) in which dietary restraint was associated with increased activity to visual food stimuli in diverse brain regions, like as the dlPFC or striatum. However, previous studies mostly had small sample sizes (Born et al., 2011; Coletta et al., 2009; Ely et al., 2014; Wang et al., 2016) and some studies used lenient multiple comparison corrections (Coletta et al., 2009; Ely et al., 2014), which is problematic as the probability of false positives is not properly controlled this way (Eklund et al., 2016). In contrast to most previous studies, the current study had a large sample size and employed a stringent multiple comparison correction.

In addition, most previous studies did not control attentional focus during food viewing (Roefs et al., 2018). However, as high-caloric palatable food is highly tasty but unhealthy, restrained eaters are unlikely to consistently focus on hedonic aspects of food, but rather alternate between a hedonic and a health attentional focus frequently. Inconsistencies in the literature might partly result from uncontrolled alternation in attentional focus. The current study controlled attentional focus with task instructions, which involved frequent switching between hedonic, health, and neutral attentional foci. Thereby, the current manipulation of attentional focus might have subsumed the effect of dietary restraint, which presumably involves frequent switching of attentional focus between hedonic and health-related aspects of food stimuli. Taken together, it appears that, under tight control of attentional focus, dietary restraint does not significantly influence brain responses to food stimuli, and suggest that transient cognitive states might be more influential in determining brain responses to food than relatively stable characteristics, like dietary restraint.

The current study has several strengths. Firstly, tight control over mental processes was achieved by having participants perform a one-back task to manipulate attentional focus, and the study was well-powered, especially for detecting within-subject effects. Furthermore, we used mass-univariate as well as multivariate analyses to not only assess involvement of brain regions but also consider information reflected in multi-voxel patterns of brain activity (Mur et al., 2009). In addition, we used food stimuli that were individually tailored on palatability and used high-caloric as well as low-caloric food stimuli. Nevertheless, the current study has some limitations. The health attentional focus was conceptualized as calorie content comparisons. This conceptualization might be an oversimplification, as there are likely other important characteristics of food stimuli that determine healthiness considerations.

Future research could use a larger set of food stimuli to test generality of findings across a larger range of food stimuli and might use representational similarity analysis techniques (Kriegeskorte, Mur, & Bandettini, 2008), in addition to classification analysis, to assess the neural representation of food characteristics more closely. Furthermore, it might also be interesting to utilize a broader conceptualization of a health attentional focus to assess its effects on neural representations of food. This might be done by assigning a subjective health score, by having participants rate food stimuli on several health aspects, depending on how important they are to them individually.

Conclusion

The current study showed that the *level* of brain activity is not proportionate to the palatability of food stimuli and hardly proportionate to the caloric content. Instead, palatability and calorie content of food stimuli could be significantly decoded from *patterns* of brain activity using MVPA. The *level* of brain activity did depend strongly on attentional focus, and was generally largest with a hedonic attentional focus. These findings – that is, the combination of a lack of significant effects of palatability and caloric value and a robust effect of attentional focus – suggest that the *level* of brain activity does not reflect stimulus valence or reward value (i.e., palatability and caloric content), but may reflect motivational salience (Roefs et al., 2018; Salamone & Correa, 2012) or reward *sensitivity*. Importantly, and contrary to hypothesis, we observed no significant correlations between brain responding and dietary restraint in healthy-weight women. This suggests that dynamic cognitive states (i.e., attentional focus) might be more influential in determining brain responses to food stimuli than relatively stable characteristics, like chronic dietary restraint. Therefore, it is highly important to exert experimental control over mental processes that participants engage in when viewing food stimuli in fMRI studies. Without clearly knowing the mental state of the participant in the different experimental conditions, drawing clear conclusions from brain activity is impossible (Poldrack, 2006, 2011). Taken together, univariate analyses of brain activity elicited by visual food stimuli is not sufficient to truly understand how our brain responds to food. Information about food palatability and calorie content is contained in *patterns* of brain activity. Importantly, the distinction between valence and salience was only possible by including palatable as well as unpalatable food stimuli.

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Author contributions

S.K., and Anne R. designed the study. S.K. and L.P. collected the data. S.K., L.P., S.F., J.H., and G.V. analyzed the data. The scanning protocol was set up by Alard R. S.K. and Anne R. wrote the manuscript, A.J., Alard R., S.F., L.P., J.H., and G.V. gave feedback on the manuscript, and all authors approved the final version.

Competing interests

The authors declare no competing financial interest.

Data and code availability

Data and code of this study are available upon reasonable request from the corresponding author at the Dutch Dataverse Network (https://dataverse.nl/).

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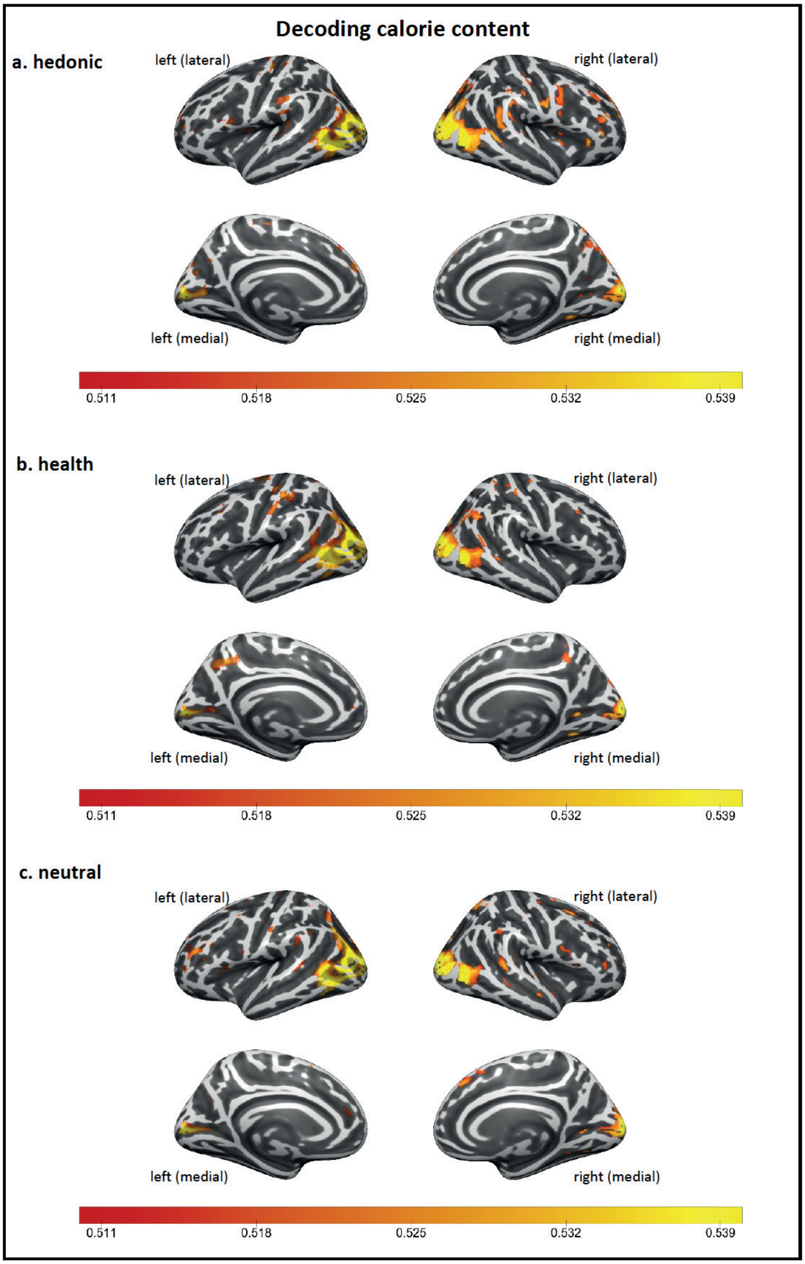
Supplementary material

Supplementary Table 1: Brain regions not related to food decision making in previous literature with decoding accuracy significantly above chance ($p < 0.05$, FDR corrected) for decoding calorie content; H = hemisphere, L = left, R = right, B = Bilateral, MNI = Montreal Neurological Institute

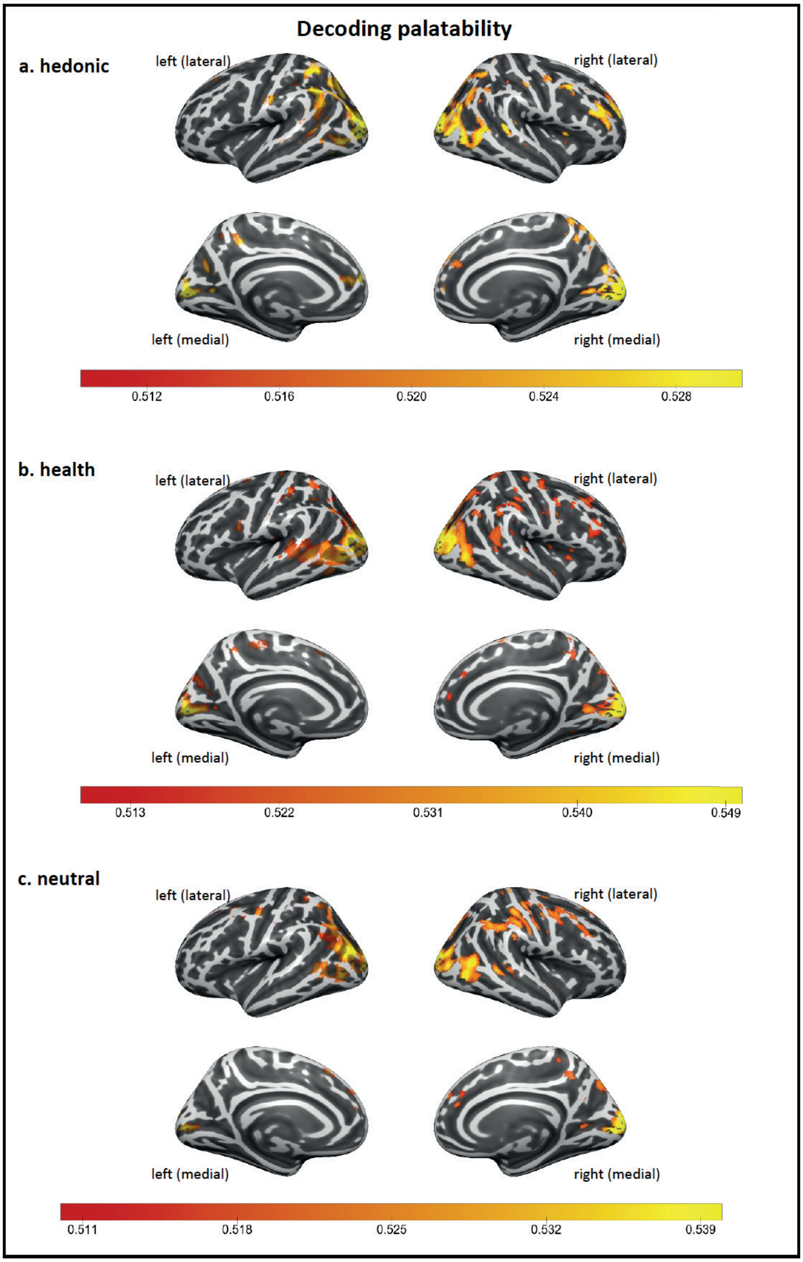
Cluster	Region	H	Cluster size	Peak coordinates (MNI)	Percentage accuracy
Decoding calorie content: across attentional foci					
1	Cerebellum	L	24	-34 -60 -30	51.49
2	Cerebellum	L	12	-10 -80 -30	51.20
3	Middle Temporal Gyrus/ Inferior Temporal Gyrus	R	40	54 -6 -24	51.13
4	Inferior Temporal Gyrus	R	1	56 -20 -22	50.74
5	Precunneus/ Middle Occipital Gyrus / Cunneus / Middle Temporal Gyrus / Lingual Gyrus / Superior Parietal Lobule/ Fusiform Gyrus/ Inferior Parietal Lobule / Inferior Occipital Gyrus/ Superior Temporal Gyrus / Angular Gyrus / Inferior Temporal Gyrus / Superior Occipital Gyrus/ Cingulate Gyrus / Supramarginal Gyrus / Postcentral Gyrus	R	15861	40 -80 0	58.28
12	Precentral Gyrus	L	1	-52 16 10	50.78
14	Superior Temporal Gyrus	R	1	44 -38 12	50.66
16	Postcentral Gyrus	R	1	60 -10 20	50.76
17	Supramarginal Gyrus/ Superior Temporal Gyrus	L	30	-50 -60 28	50.86
18	Inferior Parietal Lobule	L	2	-48 -36 22	50.92
19	Supramarginal Gyrus	L	1	-40 -52 26	50.72
20	Supramarginal Gyrus	R	1	56 -48 26	51.01
21	Inferior Parietal Lobule	L	3	-38 -48 26	50.74
22	Postcentral Gyrus/ Inferior Parietal Lobule/ Precentral Gyrus	L	446	-44 -28 42	51.80
23	Inferior Parietal Lobule/ Supramarginal Gyrus	R	19	54 -38 32	51.04
24	Precentral Gyrus	R	19	58 -14 34	51.06
25	Postcentral Gyrus/ Inferior Parietal Lobule/ Precentral Gyrus	R	789	44 -30 44	52.06
31	Precentral Gyrus	R	3	24 -14 50	50.85
32	Precentral Gyrus	R	3	34 -30 58	50.84
34	Precuneus	R	2	12 -52 62	50.67
40	Postcentral Gyrus/Precuneus	L	1	-10 -54 66	51.05

Supplementary Table 2: Brain regions not related to food decision making in previous literature with decoding accuracy significantly above chance (*p* < 0.05, FDR corrected) for decoding palatability; H = hemisphere, L = left, R = right, B = Bilateral, MNI = Montreal Neurological Institute

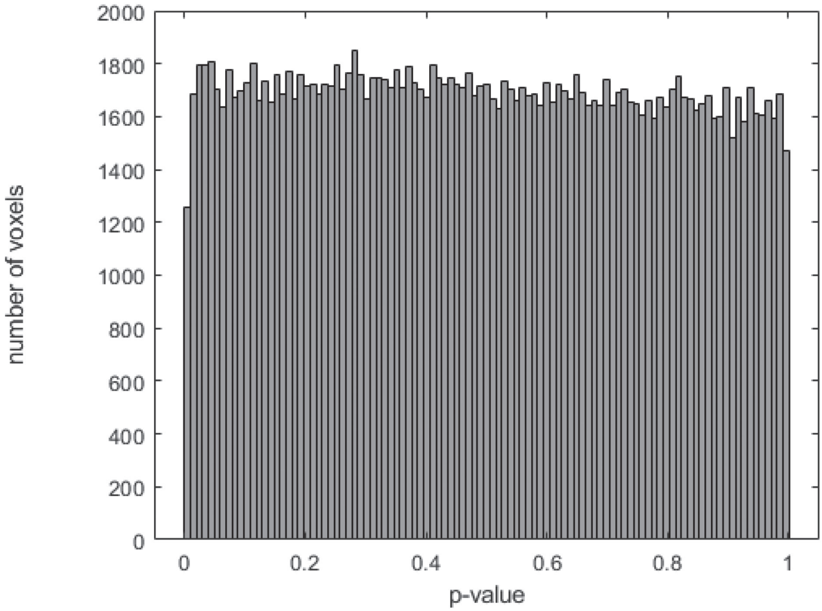
Cluster	Region	H	Cluster size	Peak coordinates (MNI)	Percentage accuracy
Decoding palatability: across attentional foci					
1	Cerebellum	R	246	36 -76 -30	51.71
2	Cerebellum	L	197	-10 -84 -32	51.47
3	Cerebellum	R	123	16 -82 -28	51.34
4	Cerebellum	L	4	-32 -60 -30	51.07
5	Cuneus/ Precuneus/ Middle Occipital Gyrus/ Middle Temporal Gyrus/ Lingual Gyrus/ Inferior Parietal Lobule/ Superior Parietal Lobule/ Supramarginal Gyrus/ Superior Temporal Gyrus/ Inferior Occipital Gyrus / Fusiform Gyrus/ Angular Gyrus/ Inferior Temporal Gyrus/ Posterior Cingulate/ Superior Occipital Gyrus/ Cingulate Gyrus	B	16301	-12 -96 2	58.22
10	Postcentral Gyrus	L	5	-58 -12 18	51.01
12	Postcentral Gyrus	L	21	-48 -12 22	50.93
13	Precentral Gyrus	L	10	-54 -4 24	51.05
14	Inferior Parietal Lobule	R	19	42 -38 26	51.03
15	Frontal Lobe White Matter	R	11	26 -42 28	50.98
16	Postcentral Gyrus/Inferior Parietal Lobule/Precentral Gyrus	L	230	-46 -30 34	51.33
18	Frontal Lobe/ Parietal Lobe White Matter	L	5	-30 -40 30	50.70
19	Inferior Parietal Lobule	R	35	38 -34 38	51.15
23	Postcentral Gyrus	R	28	52 -28 44	51.15
25	Frontal Lobe/ Parietal Lobe White Matter	R	28	26 -36 42	50.95
26	Frontal Lobe White Matter	L	7	-24 -26 44	50.84
27	Precentral Gyrus	R	7	44 -12 40	50.87
28	Precuneus	R	9	10 -54 46	50.82
29	Precentral Gyrus	R	53	28 -24 48	51.14
37	Frontal Lobe White Matter	L	8	-16 -20 58	51.08
42	Frontal Lobe White Matter	L	1	-16 -24 58	50.89
44	Superior Parietal Lobule/ Precuneus	L	9	-14 -62 60	51.06
45	Precentral Gyrus	R	1	32 -20 60	50.92
47	Precentral Gyrus	L	4	-32 -22 62	50.71
49	Postcentral Gyrus	R	7	24 -42 68	50.98
50	Postcentral Gyrus/ Precentral Gyrus	L	30	-26 -32 68	51.27



Supplementary Figure 1: Clusters with decoding accuracy significantly above chance for decoding calorie content ($p < 0.05$, FDR corrected); a: in hedonic attentional focus, b: in health attentional focus, c: in neutral attentional focus; visualizations were created using FreeSurfer and Surf Ice



Supplementary Figure 2: Clusters with decoding accuracy significantly above chance for decoding palatability ($p < 0.05$, FDR corrected); a: in hedonic attentional focus, b: in health attentional focus, c: in neutral attentional focus; visualizations were created using FreeSurfer and Surf Ice



Supplementary Figure 3: Distribution of p-values for contrast palatable > unpalatable

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CHAPTER 3

Effects of Mindset and Dietary Restraint on Attention Bias for Food and Food Intake

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Abstract

Evidence for attention bias (AB) for food in restrained eaters is inconsistent. A person's mindset related to food – that is, whether someone focuses on the hedonic or health aspects of food – might be an overlooked influence on AB for food, possibly explaining the inconsistency in the literature. Fluctuations between a hedonic versus a health mindset might be strongest in restrained eaters, who have a conflicted relationship with food. We investigated the effect of mindset and dietary restraint on AB for food and food intake. We hypothesized that AB for food, as reflected in eye-movement measures and manual response latencies, as well as food intake, would be larger in the hedonic than in the health mindset, most strongly in participants scoring high on dietary restraint. Moreover, we expected a positive correlation between AB for food and food intake, especially in the hedonic mindset. We used short video clips to induce either a health or hedonic mindset. Subsequently, participants (n = 122) performed a modified additional singleton task with pictures of high-caloric food vs neutral pictures as irrelevant distractors. Next, food intake was measured in a bogus taste test. We found no evidence for an AB towards food, nor any moderation by either mindset or dietary restraint. Food intake tended to be higher for participants scoring higher on dietary restraint, but effects were not moderated by mindset. Response-latency based AB for food tended to correlate positively with food intake in the hedonic mindset. Taken together, our hypotheses regarding AB for food were largely not confirmed. We provide suggestions on how to improve upon the specific implementations of our AB task and mindset manipulation, to strengthen future research in this field.

Keywords: mindset, dietary restraint, attentional bias, food intake, eye-tracking, bogus taste test

Introduction

The prevalence of overweight and obesity has reached an epidemic scope (Berghofer et al., 2008; Flegal, Carroll, Ogden, & Curtin, 2010; WHO, 2020), which is a cause for concern because overweight and obesity are associated with harmful health outcomes and high health care costs (Finkelstein, Ruhm, & Kosa, 2005; WHO, 2020). Today's obesogenic food environment, in which cheap and easily obtainable high-caloric food is omnipresent and heavily advertised, likely plays a role in the development and maintenance of the high prevalence of overweight and obesity (Hill & Peters, 1998; Morland & Evenson, 2009; Townshend & Lake, 2017). A common response to the obesogenic environment and the resulting weight gain is the development of dietary restraint, which is characterized by chronic weight concerns and dieting attempts (Herman & Polivy, 1980). However, dietary restraint is often unsuccessful and restrained eaters tend to have a higher body-mass-index (BMI) than unrestrained eaters (Jansen, 2016; Snoek, van Strien, Janssens, & Engels, 2008). Adhering to a diet is notoriously difficult, and long-term weight-loss maintenance is often poor (Fildes et al., 2015). It has been proposed that chronic dietary restraint and perceived food deprivation are associated with increased attractiveness of food and attentional bias (AB) for food (Brooks, Prince, Stahl, Campbell, & Treasure, 2011; Polivy & Herman, 2017).

AB for food denotes selective attentional processing of food stimuli and includes voluntary and involuntary attentional processes (Jessica Werthmann, Jansen, & Roefs, 2015). AB for food is proposed to be a factor in the development and maintenance of weight related problems (Meule & Platte, 2016), and has been suggested to affect food-related decisions. A recent meta-analysis showed that an AB for food is associated with craving, hunger, and food intake (Hardman et al., 2021). It has been proposed as well that AB for food is increased in restrained eaters (Polivy & Herman, 2017), but the empirical evidence for this suggestion is inconclusive (Roefs, Houben, & Werthmann, 2015; Werthmann et al., 2015). Some studies found evidence for increased attention for food in restrained eaters (Brooks et al., 2011; Dobson & Dozois, 2004; Forestell, Lau, Gyurovski, Dickter, & Haque, 2012; Hepworth, Mogg, Brignell, & Bradley, 2010; Meule, Vogele, & Kubler, 2012; Neimeijer, de Jong, & Roefs, 2013), whereas other studies found evidence of attentional avoidance of food in restrained eaters (Hotham, Sharma, & Hamilton-West, 2012), or of an approach-avoidance pattern (Hollitt, Kemps, Tiggemann, Smeets, & Mills, 2010). Notably, several studies found no significant difference in AB for food in restrained compared to unrestrained eaters (Ahern, Field, Yokum, Bohon, & Stice, 2010; Boon, Vogelzang, & Jansen, 2000; Johansson, Ghaderi, & Andersson, 2005; Werthmann et al., 2013; Wilson & Wallis, 2013). So, overall, the picture emerging from previous empirical studies is mixed. The goal of the current study is to investigate if restrained eaters may specifically have an AB for high-caloric food when they focus on food enjoyment in a hedonic mindset. It will also be explored if early and late attentional selection are differently affected by mindset.

In line with the mixed findings in the AB-literature, it has been proposed that AB for food might best be conceptualized as a situational state instead of a relatively stable person-characteristic. That is, AB for food might be reflective of someone's current motivational state and therefore fluctuate (Papies, Stroebe, & Aarts, 2008; Roefs et al., 2015; Werthmann et al., 2015). Recently, a new method to analyze the time-series of attention bias over the course of an experimental task, trial-level bias score (TL-BS), has been introduced (Zvielli, Bernstein, & Koster, 2015). By using this method, it has been shown that AB for food fluctuates over the course of a study within participants (Liu, Roefs, Werthmann, & Nederkoorn, 2019). This attentional fluctuation, that is attention towards and away from high caloric food, might be a result of the double-sided nature of high-caloric palatable foods. On the one hand, high-caloric food has a high hedonic value because of its good taste, but on the other hand, it has a low health value, because its caloric density is associated with weight gain and negative health outcomes. People may fluctuate between focusing on hedonic and health-related aspects of high-caloric food, depending on situational and cognitive factors. That is, people may look differently at food depending on their mindset.

Mindset describes the aspects that are on the foreground of one's mind when thinking about food (Bhanji & Beer, 2012). Mindset likely fluctuates over time and these fluctuations may depend on subtle context cues (Werthmann, Jansen, & Roefs, 2016). We will investigate effects of a health mindset, which frames food in term of health-related aspects, and of a hedonic mindset, which frames food in terms of pleasurable aspects of food consumption.

Mindset may focus on any aspect of food. Mindset has been shown to affect food perception in several ways. For example, it appears that brain responses to food stimuli are influenced by mindset (Bhanji & Beer, 2012; Franssen, Jansen, van den Hurk, Roebroeck, & Roefs, 2020; Hare, Malmaud, & Rangel, 2011). When focusing on health, brain responses to health cues were increased and food choices were in favor of healthier options (Hare et al., 2011). In contrast, increased activity in the mesocorticolimbic system of the brain was observed in a hedonic attentional focus compared to a neutral attentional focus (Franssen et al., 2020). This indicates that the salience of food might depend on mindset. In addition, food intake has been shown to be influenced by mindset as well. More specifically, portion size decisions were influenced by mindset, such that smaller portions were selected in a health mindset than in a fullness mindset (Hege et al., 2018; Veit et al., 2020). Interestingly, chocolate consumption in a so-called taste test was influenced by mindset, such that participants consumed a larger amount of chocolate in a loss of control mindset compared to a control mindset (Franssen et al., 2020).

Taken together, mindset might be a crucial determinant of AB towards food. That is AB might be directed towards food in a hedonic mindset, whereas AB might be directed away from food when in a health mindset. So, an AB for food might depend on situational states rather than relatively stable person characteristics (Field et al., 2016; Roefs, Franssen, & Jansen, 2018; Roefs et al., 2015). In line with this idea, it was found that an experimentally induced health mindset reduced AB towards food in individuals with higher levels of dietary restraint (Werthmann et al., 2016).

Effects of mindset on AB for high-caloric food are likely affected by top-down factors, such as expectations, strategy and goals, and might need some time to develop, and therefore might be most pronounced in later stages of attentional processing (Roefs et al., 2015). In contrast, early stages of attention appear to be affected more by low-level non-strategic bottom-up factors, such as the physical salience of a stimulus (van Zoest, Donk, & Theeuwes, 2004) and automatic influences of reward history (Hickey & Van Zoest, 2012). Therefore, it might be beneficial to investigate early and late attentional processes separately. Analysis methods that allow for a distinction between early and late attentional processing might be most suitable to detect an effect of mindset on AB for high-caloric food.

People may not always choose their mindset deliberately, as many factors – such as culture, media, and social networks - will influence mindset (Crum & Lyddy, 2014; Crum & Zuckerman, 2017), yet mindset will influence cognition and behavior (Crum, Salovey, & Achor, 2013). It is conceivable that, especially in a hedonic mindset, food cues in the environment attract attention even when one does not have explicit eating intentions. Effects of an AB for food might be most detrimental when people have no explicit eating intentions. For example, when people are in a hedonic mindset, a chocolate advertisement on a website during a work-related web search might capture attention and trigger the urge to consume chocolate. Food consumption in such situations may lead to problematic weight gain as it is likely driven by hedonic factors rather than physiological needs. If a researcher wants to assess this type of attentional capture, a paradigm is needed in which food does not share critical features with core components required for task performance (Cunningham & Egeth, 2018). However, most previous studies on AB for food used tasks in which food is a centrally presented and therefore difficult to ignore, such as the modified Stroop task or the visual probe task (Field et al., 2016; Roefs et al., 2015; Werthmann et al., 2015). The effects observed in these studies therefore may not be ecologically valid.

Importantly, it has been shown that an entirely task-irrelevant stimulus can capture attention (Cunningham & Egeth, 2018; Forster & Lavie, 2011). That is, a stimulus that does not share any critical features with a response target could still interfere with task performance. Therefore, using an experimental paradigm in which food items are completely irrelevant for correct task performance might be most informative and ecologically valid. The current study employed a modified version of the additional singleton task (Theeuwes, Kramer, Hahn, & Irwin, 1998), which is a type of visual search task. In this task, participants need to locate and identify a neutral target stimulus presented alongside neutral filler stimuli, while a picture of a high-caloric food or a neutral item suddenly appears as a distractor. Importantly, pictures of high-caloric food or neutral pictures are completely irrelevant for correct task performance, and participants are instructed to ignore them. In this way, the current task might resemble everyday situations, in which an AB towards food might be most detrimental, more closely than tasks in which food items are a core element for task completion.

The current study aimed to assess the effect of mindset and dietary restraint on AB for high-caloric food. Therefore, we manipulated mindset to be focused on either hedonic or health-related aspects of food. We hypothesized that AB for high-caloric food, as reflected in eye-movements and manual response latencies, would be larger in a hedonic mindset than in a health mindset, most strongly in participants scoring high on dietary restraint. For our exploratory analysis, we presumed that effects of mindset were based on late top-down attention components (Roefs et al., 2015), which are observable on eye-movements (saccades) with a long onset latency (van Zoest et al., 2004; van Zoest, Hunt, & Kingstone, 2010). To assess late attention components, we grouped trials based on saccade onset latency. We expected that effects of mindset would be more pronounced on trials with slow saccade onset compared to trials with fast saccade onset.

Additionally, we were interested in the effects of mindset and dietary restraint on intake of high-caloric food, as measured in a bogus taste test. We expected that participants would consume more high-caloric food in the hedonic mindset compared to the health mindset, and that this pattern would be more pronounced in participants with high levels of dietary restraint. Additionally, we tested the hypothesis that AB for food was positively correlated with food intake, specifically in the hedonic mindset.

Method

Participants

A power analysis conducted in G-Power (Faul, Erdfelder, Buchner, & Lang, 2009; Faul, Erdfelder, Lang, & Buchner, 2007) indicated that, for detecting a medium effect size (f = 0.25) in an ANCOVA design (fixed effects, main effects, interactions) with α of .05 and power of .80, 128 participants were required. Participants were recruited via advertisements on university notification boards, the university's student research participation system, and social media. Interested individuals were screened for eligibility. One-Hundred-twenty-three non-obese women, varying on dietary restraint, took part in the study. We only recruited women because women display a higher prevalence of dieting than men (Hill, 2002) and therefore understanding effects of dietary restraint is more relevant for women. One participant was excluded from the study due to problems with eye-tracker calibration. The final sample consisted of 122 participants (BMI: *M* = 21.71, *SD* = 2.34, range 17.59 – 27.92; age: *M* = 21.22, *SD* = 2.68, range 18 - 30; dietary restraint: *M* = 13.98, *SD* = 4.99, range 3 - 26). Each participant provided written informed consent before participating. Each participant received a gift voucher of €10 or a course credit as compensation for participating and received a debriefing after the study was entirely completed. The Ethical Committee of the Faculty of Psychology and Neuroscience of Maastricht University approved the study. The study was pre-registered on AsPredicted (https://aspredicted.org/WQN_M9P). We deviated from the pre-registered dependent variables, because our design was not well suited to analyze saccade accuracy and because we used saccade latency to create bins for the exploratory time-course analysis. To replace the dependent variables we did not analyze, we analyzed the percentage of trials with a fixation on the distractor and the duration of the first fixation on the distractor, because these variables are frequently analyzed in studies using the additional singleton paradigm (e.g., Becker, 2010; van Zoest & Donk, 2005).

Materials

Questionnaires

Online screening

An online questionnaire was administered to exclude participants with severe underweight (BMI < 17.5) or obesity (BMI > 30), and participants with vision impairments who do not wear contact lenses. In addition, the questionnaire assessed dietary restraint, to pseudo-randomize participants to mindset conditions while stratifying for dietary restraint. The questionnaire contained all 11 questions of the revised Restraint Scale (Herman & Polivy, 1980), asked for height and weight, and inquired about eyesight. Questions of interest were intermixed with distractor items to obscure the purpose of the questionnaire. Lifestyle-related questions, such as “How many hours do you sleep per night on average?”, were used as distractor items.

Hunger assessment

To standardize hunger level, the participant was asked to eat a snack (such as a sandwich) two hours before participation, and to refrain from eating and drinking anything except water in the two hours preceding participation. The participant was asked to report the time of her last meal and to describe what she had eaten on that occasion. Hunger level was assessed digitally with the question: “How hungry do you feel at this moment?”, which the participant could answer on a 100 mm visual analogue scale (VAS) ranging from 0 (not hungry at all) to 100 (very hungry).

Awareness check

To assess awareness of the aim of the study, the participant was asked to answer the following question on a blank sheet of paper: “Please write down your thoughts and remarks about the experiment. What is the aim of the experiment according to you?”.

Restraint Scale

Each participant’s level of dietary restraint was determined with the revised Restraint Scale (Herman & Polivy, 1980), which includes 11 items assessing body weight concerns and dieting intentions. Note that the revised Restraint Scale measures the intention to restrict caloric intake, not actual calorie intake restriction. We used the revised Restraint Scale because we were interested in chronic on-off dieters. The minimum score of this questionnaire is 0, and the maximum is 35, with higher scores reflecting higher levels of dietary restraint. The internal consistency of the Restraint Scale in the present sample was acceptable (Cronbach’s $\alpha = 0.77$).

Apparatus

Eye-tracking

Eye movements were recorded with an Eyelink 1000 tower-mount system (1000 Hz temporal resolution, 0.01° gaze resolution, a gaze position accuracy of 0.5; SR Research Ltd., Canada), which was used with a chinrest to minimize head movements. Calibration of the eye-tracking system was performed using a nine-point calibration procedure. Saccades and fixations were defined by Eyelink 1000's online parser. An eye-position sample was considered as belonging to a saccade if its velocity exceeded 30°/sec or its acceleration exceeded 8000°/sec/sec.

Stimulus presentation

Stimuli were presented on a 32-inch monitor (Philips) with a resolution of 1920 x 1080 pixels and a refresh rate of 100 Hz. The participant was seated at a distance of 57 cm from the screen, such that 1° visual angle corresponded to approximately 1 cm.

Mindset manipulation videos

Participants were pseudo-randomly assigned to either the health mindset or hedonic mindset. The mindsets were induced by means of short video clips (of approx. 80 s duration). The clip used to induce a health mindset displayed images and short scenes of people exercising, and pictured healthy food, such as fruit bowls and salads. Short written messages such as 'be active' or 'healthy choice' were superimposed on the images. The clip used to induce the hedonic mindset depicted images and short scenes of high-caloric food, presented in an appealing manner, and showed people enjoying food together. Short written messages such as 'have a good time' or 'indulge' were superimposed on the images. Both clips were accompanied by mindset-matching instrumental music, and the participant was asked to listen to it via headphones, to increase immersion into the mindset.

Effectiveness of the mindset manipulation was assessed with six manipulation check questions, which the participant answered on 100 mm VAS. The questions were: "To what extent were you able to immerse yourself into the video clip? very low extent – very high extent" (1: *Immersion*), "How is your current mood? very good – very bad" (2: *Mood*), "How important is enjoying food to you at this moment? not important at all – very important" (3: *Enjoyment*), "How much would you like to indulge in tasty food at this moment? not at all – very much" (4: *Indulge*), "How important is health to you at this moment? not important at all – very important" (5: *Health*), "How inclined are you to choose healthy food at this moment? not inclined at all – very inclined” (6: *Healthy choice*). The questions were presented in pseudo-random order, with the first two questions always appearing first in fixed order, as these were control questions, and the remaining four questions appearing in an individualized random order.

In addition, the effectiveness of the mindset manipulation videos was tested beforehand in a pilot study in an independent sample of participants (n = 23). In this pilot study, the manipulation appeared to work as intended (see Appendix Table 4 for results of the pilot study). Participants in the hedonic mindset (M = 7.07, SD = 1.74) tended to rate the importance of enjoyment higher than participants in the health mindset (M = 5.83, SD = 1.48; $t(21)$ = 1.825, p = .082, d = 0.765). Participants in the health mindset (M = 7.59, SD = 1.21) tended to rate the importance of health higher than participants in the hedonic mindset (M = 5.60, SD = 3.00; $t(14.731)$ = 2.124, p = .051, d = 0.872).

Additional Singleton Task

Trial and block descriptions

A modified version of the additional singleton paradigm (Theeuwes et al., 1998) was used (Figure 1). The initial display was composed of six grey circles (3.7° in diameter), which were placed equally spaced (appearing on clock positions: 1, 3, 5, 7, 9, 11) on an imaginary circle with a radius of 12.6°. The six circles contained small figure-eight masks (0.2° x 0.4°). A small black fixation cross (RGB: 0 0 0, 0.4°) was presented in the middle of the imaginary circle. The display was presented for 1000 ms and the participant was instructed to fixate her gaze at the central fixation cross. After 1000 ms, circles changed color, such that five circles turned red, and one circle remained grey (= the target). The masks inside the circles that turned red changed to small letters E, F, H, P, S, or U), and to C or reverse C in the circle that remained grey (= target). The participant was instructed to make a saccade to the target circle as soon as the color change happened and to indicate if the letter in target circle was a C or reversed C via a press on a button box. In approximately 90 percent of the trials (i.e., on 288 trials), a distractor item was added to display at the time of the color change, placed on the imaginary circle at a separation of either 90° or 150° from the target circle. The distractor was a high-caloric food item half of the time (i.e., on 144 trials), and a musical instrument the other half of the time (i.e., on 144 trials). The distractor item also contained one of the small letters. The participant was told to ignore the distractor. The task was performed in two blocks of 156 trials each for a total of 312 trials. A blank screen (duration: 500 ms) was presented in between trials. The two blocks of interest were preceded by one practice block consisting of 30 trials. In ten percent of the practice trials, a red circle was used as distractor. In the other practice trials, no distractor was added to the display.

Distractor items

Seventy high resolution (96 pixels/inch) color pictures were used as distractor stimuli. Thirty-five images depicted musical instruments (neutral distractors), and 35 images depicted high-caloric food items. The displayed objects were presented on a transparent background. Stimuli had an original size of 454 x 454 pixels and were presented at size of 3.7° of visual angle. Stimuli were retrieved from the internet and from the database of the Eating Behavior Laboratory of Salzburg University (Blechert, Lender, Polk, Busch, & Ohla, 2019; Blechert, Meule, Busch, & Ohla, 2014).

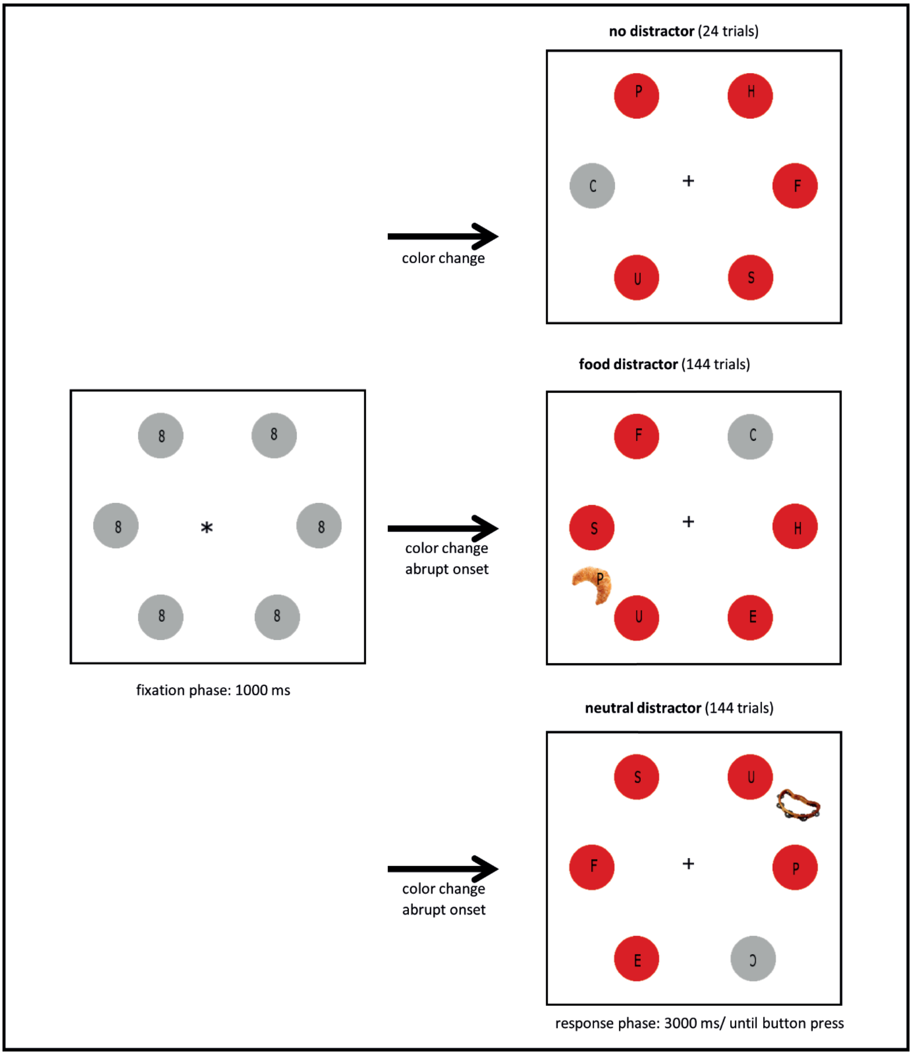

Figure 1: Modified additional singleton task; each participant performed 312 trials of this task

Bogus taste test

The participant was presented with four different types of high-caloric snack foods: salted (5.51 kcal/g) and paprika flavored (5.38 kcal/g) crisps (brand: Lay's), M&M's (5.12 kcal/g), and Maltesers (5.00 kcal/g). The foods were placed in four glass bowls (Ø 20.5 cm for crisps, Ø 13.5 cm for chocolates), which were filled generously, such that consumption of a moderate amount of food would not be easily noticeable. Bowls contained on average respectively 562.27 g of salted crisps, 572.34 g of paprika flavored crisps, 913.55 g of M&M's, and 639.77 g of Maltesers. Questionnaires to assess taste perception on 100mm VAS rating scales were placed with each bowl (e.g., "How tasty do you find the crisps?"; see Appendix for the specific questions). The participant was instructed to taste and rate the food and was given exactly ten minutes. She was told that if she was finished before this time had passed, she could taste some more of the food but was asked to not change answers on the taste perception questionnaire anymore. Unbeknownst to participants, the foods were weighed (with a precision balance PB3002 Mettler Toledo) before and after the taste test to calculate the total number of calories consumed.

Procedure

The participant was screened with an online questionnaire approximately one week before participation. At the beginning of the scheduled session, the participant was welcomed, received information about the experiment, and signed an informed consent form. Then, the participant received instructions about the additional singleton task, was seated in front of the stimulus presentation monitor, and was asked to place her head on the chinrest. Thereafter, the participant filled in the hunger assessment questionnaire. Then, the eye-tracker was calibrated. Subsequently, the practice block of the additional singleton task was performed. After the practice block, the mindset manipulation video clip was played, and the participant answered the manipulation check questions. Then, the eye-tracker was calibrated again, and this was followed by the first block of the additional singleton task. After the first block, the mindset manipulation video and the manipulation check questions were repeated to boost the manipulation. The eye-tracker was calibrated again, and the second block of the additional singleton paradigm was performed. Next, the participant was accompanied to another room for the bogus taste test, and afterwards she filled in the questionnaire on awareness of the study's aim and completed the revised restraint scale[4]. Next, height and weight of the participant were measured. Finally, the participant was thanked and received compensation for participating.

Analyses

Manipulation check

The responses to each question of the manipulation check were averaged across the measurement after the first and the second presentation of the mindset manipulation moments. The score on each question was analyzed in an ANCOVA with mindset (health vs. hedonic) as fixed factor and dietary restraint as covariate (mean-centered).

Additional singleton task

Data were preprocessed and prepared for the main statistical analyses as follows: Information about saccades and fixations were extracted from the eye-tracking data files. Interest areas around the fixation cross (1.5° in size), target (6° in size), and distractor (6° in size) were defined. Saccades and fixations were to be considered on the object if they fell into the corresponding interest area. Trials were excluded based on the following exclusion criteria: For the eye-tracking measures, trials with first saccade onset faster than 80 ms (0.926 %) or slower than 600 ms (0.899 %) were excluded from the analyses (van Zoest & Donk, 2008; van Zoest et al., 2004). In addition, trials with the first saccade not starting from within 1.5° around the fixation cross (4.517 %) were excluded from the analysis. Those criteria led to a total exclusion of 5.547 % of the trials. For manual response latency analyses, these trials were also excluded. In addition, trials without button press (0.055 %) or with wrong button press (2.731 %) were excluded from manual response latency analysis. Also, trials with a manual response latency shorter than 100 ms (0.002 %) or longer than 2000 ms (0.457 %) were excluded (e.g., Theeuwes, De Vries, & Godijn, 2003). Next, trials with a

4 Dietary restraint was measured with the revised Restraint scale during the online screening and at the end of the experiment. The dietary restraint scores measured during the online screening were used for randomization purposes. The dietary restraint scores that were measured at the end of the experiment were used in the main analyses.

manual response latency shorter than the participant's mean – 3 SD (0.002 %) or longer than mean + 3 SD (1.548 %) were excluded (e.g., Castellanos et al., 2009; Mogg, Bradley, Hyare, & Lee, 1998; Werthmann et al., 2011). These criteria led to an exclusion of an additional 4.419 % of the trials. Based on all exclusion criteria, 9.341 % of trials were excluded from manual response latency analysis. Participants of whom more than one-third of the trials had to be excluded based on these criteria were excluded from data analyses. This led to the exclusion of five participants.

The analyses of the eye-tracking measurements focused on three main dependent variables: (1) the percentage of trials in which a fixation on the distractor occurred, (2) the duration of the first fixation on the distractor, (3) the total amount of time (i.e., dwell time) that the distractor was fixated on per trial. In addition, manual response latency and response accuracy were analyzed. Each dependent variable was analyzed in a mixed ANCOVA, with distractor type (neutral vs. food; within-subjects) and mindset (health vs. hedonic; between-subjects) as fixed factors and dietary restraint as covariate (mean-centered).

Time-course analysis

It is conceivable that the effect of mindset is only apparent on later attention components, as it is likely based on top-down attention processes, and that attentional selection develops over time (e.g., van Zoest et al., 2004). To test this, exploratory analyses were performed to assess if saccadic latency (i.e., onset time of the first saccade after the color change) influenced the percentage of trials with a fixation on the distractor. Therefore, for each participant, trials were grouped into three bins (thirds of the data) according to saccadic latency (fast saccade onset, medium saccade onset, slow saccade onset). The percentage of trials with a fixation on the distractor was analyzed in a mixed ANCOVA with bin (fast, medium, slow; within-subjects), distractor type (neutral vs. food; within-subjects) and mindset (health vs. hedonic; between-subjects) as fixed factors and dietary restraint as covariate (mean-centered).

Bogus taste test

For each of the four snack foods, the amount eaten by the participant was determined and the total number of calories consumed was calculated. Total calorie intake was analyzed in an ANCOVA with mindset (health vs. hedonic; between-subjects) as fixed factor and dietary restraint as covariate (mean-centered). Furthermore, correlations between total calorie intake and the dependent eye-tracking variables (described above) as well as manual response latency were calculated. To do so, for each dependent AB variable, a bias score was computed by subtracting the mean response of trials with a neutral distractor from the mean response of trials with a food distractor. A positive bias score reflects an AB towards food, whereas a negative bias score reflects an AB away from food. Correlations between food intake and bias scores were calculated within and across mindsets.

Results

Manipulation check

As expected, participants in the health and hedonic mindset did not differ in their scores on the control items *Immersion* and *Mood*. Contrary to expectations, there was no significant difference between mindsets on *Enjoyment*. As expected, participants in the hedonic mindset scored higher on *Indulge* than participants in the health mindset. In addition, participants in the health mindset scored higher on *Health* and *Healthy choice* than participants in the hedonic mindset. Scores on *Health* and *Healthy choice* were influenced by dietary restraint, such that participants with higher levels of dietary restraint scored higher on *Health* and *Healthy choice*. None of the mindset x dietary restraint interactions reached significance. See Table 1 for all relevant statistics. Overall, three of the four relevant items showed significant differences between mindsets in line with our expectations. Thus, it appears that our mindset manipulation was effective, as evidenced by medium to large effect sizes on relevant items.

Table 1: Mindset manipulation check results; ***** = trend-level significant at *p* < .10, ****** = significant at *p* < .05, ******* = significant at *p* < .01; *M*: mean, *SD*: standard deviation, *d*: Cohen's d

Item		***M* (*SD*)**	**mindset**			**dietary restraint**		**mindset x dietary restraint**	
			F(1,118)	*p*	*d*	*F*(1,118)	*p*	*F*(1,118)	*p*
Immersion	health	67.84 (16.41)	0.012	.912	0.024	0.045	.832	0.929	.337
	hedonic	68.25 (17.55)							
Mood	health	68.60 (14.44)	0.005	.941	0.029	0.825	.365	0.102	.750
	hedonic	69.08 (18.44)							
Enjoyment	health	72.66 (16.61)	0.007	.932	0.026	0.347	.557	0.104	.747
	hedonic	72.20 (18.82)							
Indulge	health	61.10 (20.82)	4.603	.034******	0.379	0.325	.570	2.370	.126
	hedonic	69.14 (21.55)							
Health	health	77.89 (15.16)	5.779	.018******	0.474	8.639	.004*******	0.830	.364
	hedonic	68.65 (23.07)							
Healthy choice	health	74.70 (15.33)	23.104	.000005*****	0.887	15.022	.0002*******	2.596	.110
	hedonic	57.04 (23.62)							

Hunger check

Overall, participants reported moderate hunger levels (*M* = 42.02, *SD* = 26.42). On average, participants complied with the instruction to eat two hours before participation but not within the two preceding hours (average time since last eating occasion: *M* = 141.31 minutes, *SD* = 58.26 minutes). Hunger level did not differ significantly between mindsets (health: *M* = 41.33, *SD* = 26.94, hedonic: *M* = 42.70, *SD* = 26.09, *F*(1,118) = 0.049, *p* = .825). There was no significant effect of dietary restraint on hunger level (*F*(1,118) = 0.459, *p* = .500), and no significant interaction between dietary restraint and mindset (*F*(1,118) = 2.461, *p* = .119).

Dependent variables eye-tracking

Percentage of trials with fixation on distractor

Unexpectedly, overall, the neutral distractor tended to be fixated on a slightly higher percentage of trials than the food distractor (F(1,113) = 2.771, p = .099, η_p^2 = 0.024; Table 2). In addition, the distractor – independent of distractor *type* – was fixated on a greater percentage of trials in the hedonic mindset than in the health mindset (F(1,113) = 3.992, p = .048, η_p^2 = 0.034). The mindset x dietary restraint interaction was significant (F(1,113) = 4.208, p = .043, η_p^2 = 0.036) as well. Splitting the sample in restrained eaters (scoring 15 and higher on revised Restraint Scale, n = 52) and unrestrained eaters (scoring 14 or lower on the revised Restraint Scale, n = 65) showed that for unrestrained eaters the percentage of trials with a fixation on the distractor was higher in the hedonic mindset (M = 16.06, SD = 14.64) than in the health mindset (M = 10.21, SD = 6.95; t(43.999) = 2.049, p = .046, d = 0.511), but did not differ significantly for restrained eaters (health: M = 9.94, SD = 6.53; hedonic: M = 11.02, SD = 7.44; t(50) = 0.557, p = .58, d = 0.154). No other effects reached significance, all F(1,113) < 2.377, all p > .126. See Table 2 for an overview of the statistics.

Two participants in the hedonic mindset had a high percentage of fixations on the distractor (> M + 3 SD). When removing these participants from the analysis, the neutral distractor still tended to be fixated on a higher percentage of trials than the food distractor (F(1,111) = 3.845, p = .052, η_p^2 = 0.033. The main effect of mindset (F(1,111) = 2.036, p = .156, η_p^2 = 0.018) and the mindset x dietary restraint interaction (F(1,111) = 2.314, p = .131, η_p^2 = 0.020) were no longer significant. No other effects were significant after removing these two participants, all F(1,113) < 2.429, all p > .122.

First fixation duration and dwell time on distractor

No significant effects on the duration of the first fixation on the distractor were detected, all F(1,111) < 1.873, all p > .174. Similarly, no significant effects on the dwell time on the distractor were observed, all F(1,111) < 2.086, all p > .151. See Table 2 for an overview of the statistics. Overall, the results on the eye-tracking dependent variables were not in line with our hypotheses, as we observed no attentional bias for food, and no moderation by either dietary restraint or mindset.

Manual response latency

No significant effects on manual response latency were found, all $F(1,113) < 2.099$, all $p > .15$. See Table 2 for an overview of the statistics. The results on manual response latency were not in line with our hypotheses, as we observed no attentional bias for food, and no moderation by either dietary restraint or mindset.

Response accuracy

As expected, response accuracy did not differ significantly between conditions, all $F(1,113) < 1.255$, all $p > .265$. See Table 2 for an overview of the statistics.

Time-course analyses

Percentage of trials with fixation on distractor

We analyzed the percentage of trials with a fixation on the distractor as a function of saccade latency (grouped in 3 bins: slow, medium, fast) to explore effects of mindset on attentional selection. The percentage of trials with a fixation on the distractor differed significantly across bins ($F(1.278,144.389) = 155.739$, $p < .001$, $\eta_p^2 = 0.580$)[5], with lower percentages with increasing bin. We also observed a significant interaction between bin and distractor type ($F(1.806,204.069) = 3.525$, $p = .036$, $\eta_p^2 = 0.030$). Against our expectations, in bin 1 (fast), the neutral distractor ($M = 22.87$, $SD = 17.09$) was fixated on a higher percentage of trials than the food distractor ($M = 20.94$, $SD = 16.02$; $t(116) = 2.586$, $p = .011$, $d = 0.116$). There was no significant difference in the percentage of trials with a fixation on the distractor between neutral and food distractors in bin 2 (medium; neutral: $M = 9.37$, $SD = 9.93$; food: $M = 9.07$, $SD = 11.53$; $t(116) = 0.502$, $p = .616$, $d = 0.028$) and bin 3 (slow; neutral: $M = 4.37$, $SD = 6.78$; food: $M = 4.59$, $SD = 7.54$; $t(116) = 0.522$, $p = .602$, $d = 0.031$). Furthermore, as in the main analysis, participants in the hedonic mindset ($M = 13.85$, $SD = 12.22$) fixated the distractor – independent of distractor *type* – on a higher percentage of trials than participants in the health mindset ($M = 10.04$, $SD = 6.68$; $F(1,113) = 4.002$, $p = .048$, $\eta_p^2 = 0.034$). Also, as in the main analyses, the mindset x dietary restraint interaction was significant ($F(1,113) = 4.212$, $p = .042$, $\eta_p^2 = 0.036$). No other effects reached significance, all $F < 2.693$, $p > .104$. See Figure 2 for the pattern of results.

5 Results involving the factor bin are reported with Greenhouse-Geisser correction.

Table 2: Overview of effects from analysis of additional singleton task; ***** = trend-level significant at $p < .10$, ****** = significant at $p < .05$; *M*: mean, *SD*: standard deviation

	percentage of trials with fixation on distractor		**duration of first fixation on distractor**		**dwell time on distractor**		**manual response latency**		**response accuracy**	
Descriptive statistics	***M (SD)***		***M (SD)***		***M (SD)***		***M (SD)***		***M (SD)***	
	neutral	**food**	**neutral**	**food**	**neutral**	**food**	**neutral**	**food**	**neutral**	**food**
health	10.62 (6.67)	9.55 (7.33)	86.38 (22.86)	91.51 (28.14)	94.84 (30.11)	100.49 (40.02)	797.48 (139.96)	795.82 (145.15)	97.07 (2.55)	97.14 (2.59)
hedonic	14.03 (11.97)	13.78 (12.92)	84.48 (22.07)	85.22 (24.86)	92.45 (30.23)	95.23 (34.62)	803.05 (114.30)	802.01 (116.23)	97.26 (1.88)	97.51 (1.83)
Inferential statistics	***F***(1,113) ***(p)***		***F***(1,111) ***(p)***		***F***(1,111) ***(p)***		***F***(1,113) ***(p)***		***F***(1,113) ***(p)***	
distractor	2.771 (.099*****)		1.610 (.207)		1.990 (.161)		0.578 (.449)		0.987 (.323)	
mindset	3.992 (.048******)		0.833 (.363)		0.290 (.592)		0.030 (.863)		0.651 (.421)	
dietary restraint	1.883 (.173)		0.649 (.422)		1.265 (.263)		0.566 (.454)		1.255 (.265)	
distractor x mindset	0.808 (.371)		0.734 (.393)		0.131 (.718)		0.003 (.954)		0.428 (.515)	
distractor x dietary restraint	2.377 (.126)		1.873 (.174)		1.840 (.178)		2.099 (.15)		0.643 (.424)	
mindset x dietary restraint	4.208 (.043******)		0.043 (.836)		0.305 (.582)		0.032 (.859)		0.000009 (.998)	
distractor x mindset x dietary restraint	0.049 (.825)		0.203 (.654)		0.578 (.449)		0.590 (.444)		0.120 (.730)	

After removing two participants with a rather high percentage of fixations on the distractor (> *M* + 3 *SD*), we still observed significant differences in percentage of trials with a fixation on the distractor between bins (F(1.223,135.727) = 153.099, $p < .001$, $\eta_p^2 = 0.580$). Also the interaction between bin and distractor type remained trend-level significant (F(1.799,199.692) = 3.074, $p = .054$, η_p^2 = 0.027). Also, participants tended to fixate more often on the neutral compared to the food distractor (F(1,111) = 3.767, $p = .055$, $\eta_p^2 = 0.033$). No other effects were significant after removing the two participants, all $F < 2.41$, all $p > .123$.

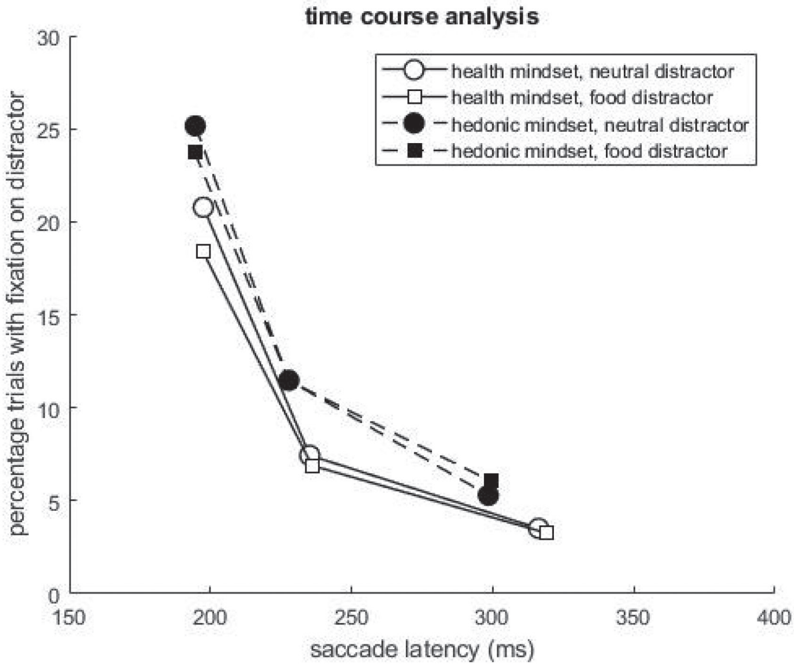

Figure 2: Results of the time course analysis depicting the percentage of trials with a fixation on the distractor per saccade latency bin

Bogus taste test

We observed a trend-level effect of dietary restraint on food intake during the taste test (F(1,113) = 3.068, $p = .083$, $\eta_p^2 = 0.026$), reflecting increased food intake with increased dietary restraint. Contrary to our hypothesis, food intake during the taste test did not differ significantly between mindsets (health: M = 288.46 kcal, SD = 157.1; hedonic: M = 265.33, SD = 150.81 kcal; $F(1,113)$ = 0.424, p = .516, η_p^2 = 0.004), and the dietary restraint x mindset interaction was not significant ($F(1,113)$ = 1.479, p = .226, η_p^2 = 0.013).

Correlations AB scores with food intake

Across mindsets, no significant correlations between AB scores and food intake were observed, all r < .089, all p > .353. In the health mindset, no significant correlations between AB scores and food intake were observed either, all r < .157, all p > .243. In the hedonic mindset, we observed a trend-significant correlation between the percentage of fixation on the distractor bias score and food intake ($r(54)$ = .231, p = .093), indicating that this AB towards food tended to be positively associated with a higher food intake during the taste test. However, when removing two participants with a rather high percentage of fixations on the distractor (> M + 3 SD), the correlation was no longer significant ($r(52)$ = .174, p = .218). We also observed a trend-level correlation between manual response latency bias and food intake ($r(54)$ = .245, p = .075), indicating that this AB towards food tended to be positively associated with a higher food intake during the taste test as well. Other AB scores (i.e., first fixation duration bias score, dwell time bias score) were not significantly correlated with food intake (range r -.050 - -.015, all p > .722).

Correlations mindset manipulation scores with food intake

Across mindsets, scores on *Immersion* tended to correlate positively with food intake during the taste test ($r(117)$ = .175, p = .059). Scores on *Enjoyment* correlated significantly positively with food intake ($r(117)$ = .184, p = .047), indicating that participants scoring higher on *Enjoyment* consumed more food. Similarly, scores on *Indulge* correlated significantly positively with food intake during the taste test ($r(117)$ = .238, p = .010), indicating that participants scoring higher on *Indulge* consumed more food. No other correlations across mindsets reached significance, range $r(117)$ -.100 – .055, all p > .282.

In the health mindset, we observed a significant correlation between scores on *Indulge* and food intake ($r(58)$ = .339, p = .009), indicating that participants with higher scores on *Indulge* consumed more food. We also observed a marginally significant negative correlation between scores on *Health* and food intake ($r(58) = -.222$, $p = .093$), indicating that participants with higher scores on *Health* tended to consume less food. No other correlation reached significance in the health mindset, all $r(58) < .215$, all $p > .105$.

In the hedonic mindset, we observed a significant correlation between scores on *Immersion* and food intake ($r(59) = .282$, $p = .031$). We also observed a significant correlation between scores on *Enjoymen*t and food intake ($r(59) = .307$, $p = .018$), indicating that participants with higher scores on *Enjoyment* consumed more food. No other correlations reached significance in the hedonic mindset, range $r(59)$ -.069 - .179, all $p > .174$.

Discussion

The current study tested the hypothesis that participants would display a larger attention bias for high-caloric food and consume more food in the hedonic mindset than in the health mindset, most strongly in participants scoring high on dietary restraint. In addition, we explored if effects of mindset on AB for food are more pronounced on trials with a slow saccade onset. Finally, we expected that AB for food would correlate positively with food intake in the bogus taste test, especially in the hedonic mindset. The main findings include: First, the results showed no evidence for AB for food. Second, we observed no significant effect of mindset or dietary restraint on AB for food. Third, whereas mindset did not significantly affect food intake, participants scoring higher on dietary restraint tended to consume more high-caloric food during the bogus taste test. Fourth, in the hedonic mindset, manual response-latency based AB for food (but not other indicators of AB for food) tended to correlate positively with food intake during the bogus taste test.

Contrary to our hypothesis, we did not observe an AB for food at all in the present experiment. Overall, participants' attention was captured by the irrelevant distractor (food and neutral) on a small percentage of trials only (on average on 11.91% trials). Other studies have similarly reported lack of evidence for AB for food. For example, in a Posner cueing task, no AB for food was found (Soetens, Braet, & Bosmans, 2008). Also, when investigating AB for food in overweight vs. lean individuals with a modified additional singleton task, no AB for food was observed on eye-tracking measures (Pimpini, Kochs, van Zoest, Jansen, & Roefs, 2022). In contrast to studies that failed to find evidence for a bias for food, studies that have reported an overall AB towards food typically used the dot-probe task to measure AB for food (Werthmann et al., 2015). However, recent work using an online version of dot-probe task also failed to observe an AB for food (Liu, Roefs, & Nederkoorn, 2021). One explanation why the current study failed to observe an AB for food may be because the task was too easy, due to the ratio of distractor present vs. distractor absent trials (90 % vs. 10% of trials), which might have benefited the ability to overcome distraction (e.g., Sayim, Grubert, Herzog, & Krummenacher, 2010). Moreover, the distractor was highly distinct from the remainder of the stimulus display, including the target (Gaspelin, Leonard, & Luck, 2017; Poiese, Spalek, & Di Lollo, 2008), also making the task potentially too easy.

Unexpectedly, mindset did not significantly affect AB for food or food intake. Perhaps, the current mindset manipulation was not sufficient to affect AB for food because it was not directly relevant for task completion and the participant was not actively involved in creating the mindset. In another study a non-task-based passive mindset manipulation has also been (partly) ineffective (Franssen et al., 2022; Pimpini et al., 2022). Note that in some previous studies (Roefs et al., 2006; Werthmann et al., 2016) a non-task-based mindset manipulation was effective, which might be because the participant had an active role in the manipulation (e.g., devising a healthy menu). However, most previous studies that have reported effects of mindset on cognitive variables (Bhanji & Beer, 2012; Franssen et al., 2020) used a mindset manipulation that was part of the experimental task. In these studies, participants were required to evaluate food stimuli throughout the task based on either hedonic or health aspects of the food stimuli to induce a mindset. So, we most likely were not able to observe effects of mindset on AB for food – if at all present – due to the passive non-task-based mindset manipulation.

The present study revealed no significant effect of dietary restraint on AB for food. This finding is in line with previous studies that observed no effect of dietary restraint on AB for food (Ahern, Field, Yokum, Bohon, & Stice, 2010; Boon, Vogelzang, & Jansen, 2000; Johansson, Ghaderi, & Andersson, 2005; Werthmann et al., 2013; Wilson & Wallis, 2013), but contradicts studies that found evidence for an effect of dietary restraint on AB for food (Forestell, Lau, Gyurovski, Dickter, & Haque, 2012; Hepworth, Mogg, Brignell, & Bradley, 2010; Meule, Vogele, & Kubler, 2012; Neimeijer, de Jong, & Roefs, 2013). Based on previous literature (Werthmann et al., 2016), we did expect to observe an interaction between mindset and dietary restraint on AB for food. We expected that AB for food would be increased in the hedonic mindset particularly in restrained eaters. It is likely that we were unable to observe the hypothesized interaction because our mindset manipulation was not task-based and did not actively involve the participant. A more involving mindset manipulation might help to resolve the unclarity. In addition, some suboptimal parameters of the paradigm used to assess AB for food might have contributed to the lack of effect.

It is to be noted that unrestrained eaters fixated the distractor, independent of whether the distractor was a food or neutral item, more often in the hedonic than in the health mindset, whereas we observed no significant difference in percentage of fixations on the distractor between mindsets in restrained eaters.[6] This suggests that in the current task, in which the distractor was a high-caloric food item half of the time, being in a hedonic mindset might have generally increased distractibility in unrestrained eaters. Recently, increased distractibility in a hedonic mindset compared to a health mindset was also observed in individuals with obesity (Pimpini et al., 2022). Thus, mindset could affect attentional settings more generally rather than specifically affecting AB for food.

Participants scoring high on dietary restraint tended to consume more food during the bogus taste test. This finding is surprising, especially considering some previous studies showing that restrained eaters consumed *less* food than unrestrained eaters during taste tests when no pre-load (such as a high-caloric milkshake) was given. However, other studies have shown that consumption of an actual pre-load is not always necessary for restrained eaters to feel disinhibited and increase their food intake. Food cues, such as the smell of food, appear to be sufficient to trigger increased food intake (Fedoroff,

6 However, the effect was no longer significant after removing two participants with a rather high percentage of fixations on the distractor. Hence, the effect does not seem to be very robust.

Polivy, & Herman, 2003; Jansen & Van den Hout, 1991; Polivy & Herman, 2017). In the present study, the food cues in the additional singleton task, which preceded the bogus taste test, might potentially have had a disinhibiting effect on restrained eaters and elicited increased food consumption. In addition, it has been shown that the eating behavior of restrained eaters is influenced by external cues, such as social norms (Ruderman, 1986). The test foods during the current bogus taste test were presented in very large bowls, such that a large quantity of food was available for the participants. Though this is common practice in bogus taste tests, this might have evoked the idea in restrained eaters that increased consumption is acceptable or even expected. Thus, cues in the study might have influenced restrained eaters more than unrestrained eaters to increase their food intake.

Interestingly, in the hedonic mindset we observed a positive trend-level correlation between manual response-latency based AB for food and food intake during the bogus taste test.[7] This is in line with the results of a recent meta-analysis (Hardman et al., 2021), which detected a relation between AB for food and food intake. Thus, AB for food might be an indicator of food-related motivation and could be predictive of subsequent food intake. Interestingly, we observed the correlation between manual response-latency based AB for food and food intake only in the hedonic mindset. So, it might be that AB for food only indicates subsequent food intake when it is in line with people's mindset. We also observed that responses to the mindset manipulation check questions were correlated with food intake during the taste test. A higher importance of food enjoyment and intention to indulge were associated with higher food intake, across as well as within mindsets, whereas higher importance of health was associated with reduced food intake, particularly in the health mindset. Also, immersion in the mindset was associated with increased food intake, especially in the hedonic mindset. This suggests that food intake might be congruent with a person's mindset and its resulting intentions.

Though the manipulation of mindset was quite effective, as evidenced by the manipulation check, future research could improve the manipulation of mindset. Especially a manipulation that is embedded in the task to measure

7 However, we observed no significant correlations between other indicators of AB for food and food intake during the bogus taste test.

AB might be more effective than the current non-task-based mindset manipulation. Additionally, it might be important that the participant is actively involved in the mindset manipulation for it to have a lasting effect. In addition, some parameters of the current task have been suboptimal. This might be a reason why we have been unable to detect distracting effects of food, especially because food was irrelevant for task completion. Future research needs to improve the parameters of the additional singleton task, to test if this paradigm is suitable to study food related AB. The current results suggest that an increase of the difficulty of the task could improve the sensitivity, which could be achieved by decreasing the likelihood of distractor presence and increasing the similarity between distractors and the remainder of the search display. Overall, more research with further refined methodology is needed before conclusions considering the effect of mindset (in interaction with dietary restraint) on AB for food can be made.

Data and code availability

Data and code of this study can be viewed at: https://osf.io/2bmeu/?view_only=91f24051a4404799bf8a5883ab79fe73.

Conflicts of interest

The authors declare no competing interests.

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Author contributions

S.K., L.P., W.v.Z., and A.R. designed the study. S.K. collected the data. S.K., L.P., and A.R. analyzed the data. S.K., W.v.Z., and A.R. interpreted the data. S.K. and A.R. wrote the manuscript. All authors gave feedback on the manuscript and approved the final version.

Appendix

Table 3: Mock taste test questions: words printed in italics are placeholders for terms that differed on each form and described the actual food item to be rated

Question	**Answer (VAS scale: 0 – 100 mm)**
How appealing do you think the *food items* look?	not appealing at all - extremely appealing
How delicious do you think the *food items* smell?	not delicious at all - extremely delicious
How tasty do you find the *food items*?	not tasty at all - extremely tasty
How *crispy/crunchy* do you find the *food items*?	not *crispy/crunchy* at all - extremely *crispy/crunchy*
How *salty/sweet* do you find the *food items*?	not *salty/sweet* at all - extremely *salty/sweet*
How long does the taste of the *food items* stay in your mouth?	not long at all - extremely long
Which of the two types of the *food item* do you like best? (asked on every second form)	a. The *item* in bowl 1 b. The *item* in bowl 2 c. I do not have a preference

Table 4: Mindset manipulation pilot results; * = trend-level significant at $p < .10$; *M*: mean, *SD*: standard deviation

Item	**health** ***M*** **(*SD*)**	**hedonic** ***M*** **(*SD*)**	***t*(21)**	***p***
To which extent were you able to get into the spirit of the movie?	6.03 (2.04)	6.90 (1.69)	-1.11	.280
How strongly are you immersed in the movie at this moment?	5.78 (1.27)	6.02 (1.41)	-0.413	.648
How hungry do you feel right now?	4.42 (2.32)	6.20 (2.71)	-1.691	.106
How sated do you feel right now?	5.32 (2.11)	5.59 (2.25)	-0.291	.774
How important is the taste of food to you at this moment?	5.81 (2.25)	6.48 (2.35)	-0.703	.490
How important is enjoying food to you at this moment?	5.83 (1.48)	7.07 (1.74)	-1.825	.082*
How much would you like to indulge in tasty food at this moment?	4.80 (2.27)	6.49 (2.66)	-1.630	.118
How important is the calorie content of food to you at this moment?	6.18 (2.01)	4.38 (2.95)	1.771	.101
How important is health to you at this moment?	7.59 (1.21)	5.60 (3.00)	2.124	.051*
How inclined are you to choose healthy food at this moment?	7.24 (1.53)	5.47 (2.82)	1.824	.080*

4

CHAPTER 4

If Anything, Dietary Restraint is Associated with Reduced Distraction by Food

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5

CHAPTER 5

General discussion

Summary and general discussion

General goal and hypotheses

In the present thesis, we tested the effects of mindset/attentional focus, hunger, and dietary restraint on brain responses to food, attention bias (AB) for food, and food intake. We expected that brain responses in the mesocorticolimbic system in response to high-caloric palatable food would depend on attentional focus, such that brain activity level would be highest in a hedonic attentional focus. We expected attentional focus related differences in brain responses to high-caloric palatable food to be most pronounced in participants with high levels of dietary restraint. Furthermore, we expected that AB for food and food intake would be influenced by mindset, such that it is increased in a hedonic mindset compared to a health mindset. We expected effects of mindset to be more pronounced in people with high levels of dietary restraint. In addition, we expected that participants with high levels of dietary restraint would show an increased AB for high-caloric food, especially in a hungry state. This chapter will provide an overview and discussion of the main findings of this thesis. In the following, effects of mindset/attentional focus, hunger and dietary restraint will be discussed for each dependent variable separately, that is brain responses to food, AB for food, and food intake.

Summary and discussion of results

Brain responses to food

In chapter 2, we assessed the effects of attentional focus and dietary restraint on brain responses to food. To do so, we presented images of food to participants with varying levels of dietary restraint while brain activity was measured with functional magnetic resonance imaging (fMRI). The food images displayed high-caloric and low-caloric food, which was individually tailored on palatability, such that highly palatable and highly unpalatable food items were presented to the participant. The images were embedded in a one-back task that was used to manipulate attentional focus. In this way, three attentional foci were induced for each participant: a hedonic attentional focus (conceptualized as taste comparisons), a health attentional focus (conceptualized as calorie content comparisons), and a neutral attentional focus (conceptualized as color comparisons). Data were analyzed using univariate as well as multivariate analysis approaches.

Univariate approach

Univariate fMRI analysis, in which a separate analysis was performed for each voxel, was used to assess how effects of attentional focus, calorie content, palatability and dietary restraint are reflected in brain activity level. We detected no brain regions with significant differences in activity level between palatable and unpalatable food stimuli. In addition, we detected only few and small differences in activity level between high-caloric and low-caloric food items. That is, we observed four small clusters, located in inferior frontal gyrus, parahippocampal gyrus, and temporal lobe, in which brain activity level was higher for high-caloric food than for low-caloric food.

Interestingly, we observed that brain activity level was strongly influenced by attentional focus. We observed 28 clusters in which activity level differed significantly between attentional foci. In many of those clusters, located mostly in prefrontal cortical regions (e.g., precuneus/cingulate gyrus, middle frontal gyrus, inferior frontal gyrus, superior frontal gyrus, anterior cingulate cortex), the brain responded stronger in the hedonic attentional focus than in the health or neutral attentional focus. However, we also observed a few regions, located among other is fusiform gyrus and inferior frontal gyrus, in which the response was stronger in the neutral attentional focus than in the health attentional focus or hedonic attentional focus.

These findings generally fit with previous observations showing that brain activity level is influenced by mindset (e.g., Bhanji & Beer, 2012; Franssen, Jansen, van den Hurk, Roebroeck, & Roefs, 2020; Hare, Malmaud, & Rangel, 2011), thereby emphasizing that brain responses to food strongly depend on the current cognitive state, and not so much relate to relatively stable person characteristics. However, the lower activity level in the health attentional focus compared to the hedonic attentional focus in the current study differs from previously observed effects of a health attentional focus. This discrepancy could stem from different ways of manipulating attentional focus and differing analysis approaches.

Importantly, mindset was not considered in many previous studies that investigated brain responses to food. Most previous studies presented stimuli in a passive viewing design (e.g., LaBar et al., 2001; Martin et al., 2010; Rothemund et al., 2007). Therefore, researchers were unaware of the mental processes that participants engaged in during scanning and only assumed that participants focused on rewarding aspects of food. The common interpretation of brain activity in these studies, that a higher level of brain activity in response to food reflects increased reward value, is based on reverse inferences (i.e., inferring mental states from brain activity) and hence might not be valid (Poldrack, 2006, 2011). Furthermore, in many previous studies palatable food items were contrasted with neutral objects. In this way, the presented stimuli differed in reward value as well as in salience. That is, palatable food is high in reward value and in salience whereas neutral objects are low in reward value and in salience. So, reward value and salience are confounded when contrasting palatable food items with neutral objects (Kahnt, 2018; Kahnt, Park, Haynes, & Tobler, 2014; Kahnt & Tobler, 2017). In the current thesis, we disentangled reward value and salience of food items by contrasting highly palatable food items, which are *high* in *reward value* and *high* in *salience*, with highly unpalatable food items, which are *low* in *reward value* and *high* in *salience*. So, we contrasted food types that strongly differ in reward value but not in salience, as both positive and negative stimuli are highly salient (Kahnt, 2018; Kahnt et al., 2014; Kahnt & Tobler, 2017).

We did not observe any significant differences in brain activity level between palatable and unpalatable food. Even in a Bayesian analysis, we mostly observed evidence for the null hypothesis which states that there is no difference in brain activity level between palatable and unpalatable food stimuli. In other words, we observed no evidence for differential level of brain activity between highly rewarding and highly unrewarding food stimuli. Therefore, it is unlikely that the reward value of food is reflected in average brain activation level. Instead, we observed that brain activity level was strongly influenced by attentional focus. In most brain regions, the highest activity level was observed in the hedonic attentional focus. Presumably, food is more salient in the hedonic attentional focus than in the health attentional focus or the neutral attentional focus, because in the hedonic attentional focus eating pleasure is at the forefront of one's mind, which makes food a highly salient stimulus. This suggests that brain activity reflects the motivational salience of food rather than the reward value. So, the theory which states that increased brain activity level in response to food reflects increased reward value of food (Giuliani, Merchant, Cosme, & Berkman, 2018) appears to be flawed, because it would require observing differences in activity level between highly palatable and highly unpalatable stimuli. It seems that the theory is partly based on invalidated assumptions and potentially invalid inferences (i.e., reverse inference). So possibly, the precise function of the mesocorticolimbic system needs to be reconsidered (cf., Roefs, Franssen, & Jansen, 2018).

However, it must be noted that the manipulation of attentional focus was conceptualized as taste, calorie and color comparisons which alternated in quick succession. Yet, in everyday situations, many more factors will be playing a role in forming a mindset, and people will not switch between different mindsets so quickly. People will likely be in a mindset for a variable period, and internal as well as external factors will play a role in entering a mindset.

We observed no significant moderation by dietary restraint on average brain activity level in response to food stimuli in any of the analyses. This finding is not in line with some previous findings (e.g., Born et al., 2011; Coletta et al., 2009; Demos, Kelley, & Heatherton, 2011; Ely, Childress, Jagannathan, & Lowe, 2014; Wang et al., 2016; Wood et al., 2016). However, previous studies used small sample sizes and very lenient multiple comparison corrections. So, these studies suffer from low power and increased risk of false positives. In addition, previous studies rarely considered mindset or other state factors, and therefore restrained and unrestrained eaters might have differed on these state factors, which could have gone unnoticed. The current results suggest that dietary restraint (trait) is less influential on brain responses to food than mindset (state).

Multivariate approach

Multi-Voxel Pattern Analysis (MVPA) is sensitive to differences in *patterns* of brain activity, whereas univariate analysis can only detect differences in average activation level (Mur, Bandettini, & Kriegeskorte, 2009). We used MVPA to assess if it was possible to decode palatability and calorie content of food items. This was done with a whole brain analysis using a searchlight consisting of 100-voxel spheres with a linear support vector machine (SVM) classifier. We were able to decode palatability as well as calorie content with decoding accuracy significantly above chance level in several regions of the mesocorticolimbic system (e.g., inferior frontal gyrus, middle frontal gyrus, superior frontal gyrus, anterior cingulate cortex, insula). This was possible across attentional foci as well as within each attentional focus, but we observed no significant differences in decoding accuracy between attentional foci. So, MVPA revealed that the brain represents palatability and calorie content of food in multi-voxel patterns of activity, rather than in average activation level. The absence of differences in decoding accuracy between the different attentional foci suggests that the representation of palatability and calorie content is of a rather general nature, unaffected by differences in perspective on food, as induced by the attentional focus manipulation. Overall, the current findings suggest that food characteristics are reflected in patterns of brain activity whereas perspectives on food are reflected in the level of brain activity.

The current findings are in line with the findings of previous studies that have shown that valence is represented in multi-voxel activity patterns, but not in level of brain activity (Chikazoe, Lee, Kriegeskorte, & Anderson, 2014). Similarly, it has been shown that food value is represented in multi-voxel activity patterns (Suzuki, Cross, & O'Doherty, 2017). In addition, also a previous study has observed that average brain activity level did not differ between palatable and unpalatable food items in a sample of participants with overweight, but was strongly influenced by attentional focus (Franssen et al., 2020). Also in this study, food palatability could be decoded above chance using MVPA. However, in this study decoding accuracy was higher in the hedonic attentional focus than in the health attentional focus. Taken together, it appears that MVPA is necessary to discover how the brain represents food value and characteristics. These aspects are not reflected in the level of brain activity. Instead, the level of brain activity reflects the perspective on food and the salience of food.

AB for food

We investigated AB for food in chapters 3 and 4 of this thesis. In chapter 3, we measured manual response latencies and eye-movements to test if mindset and dietary restraint affect AB for food. We employed a visual search task (additional singleton task; Theeuwes, Kramer, Hahn, & Irwin, 1998) in which irrelevant distractors, food or neutral images, were presented. To quantify AB for food, we measured manual response latencies and the eye-movement measures: percentage of fixations on the distractor, duration of the first fixation on the distractor, and total dwell time on the distractor. We did not observe any evidence of a manual response latency-based AB for food in general, and we also observed no effects of mindset or dietary restraint on manual response latency-based AB for food. There were also no significant effects on duration of the first fixation on the distractor and total dwell time on the distractor. We only observed a trend-level effect of distractor type on percentage of fixations on the distractor, indicating that the neutral distractor was fixated more often than the food distractor, irrespective of mindset and dietary restraint. In addition, we observed that participants in the hedonic mindset fixated the distractor (both food and neutral) more often than participants in the health mindset. This effect was more pronounced for unrestrained eaters than for restrained eaters, possibly suggesting increased distractibility in unrestrained eaters in the hedonic mindset. However, the effect of mindset as well as the interaction between mindset and dietary restraint disappeared after removing two participants with very high percentage of fixations in hedonic mindset and therefore cannot be considered robust.

The results suggest that participants do not display an AB for food. If anything, it is rather that all participants show an AB away from food. These results are not in line with some previous research, in which all participants generally displayed an AB for food, thus all participants paid more attention to food than to neutral stimuli (e.g., Werthmann, Jansen, & Roefs, 2016; Werthmann et al., 2013). However, also some other studies did not detect an AB for food in participants in general (Liu, Roefs, & Nederkoorn, 2021; Pimpini, Kochs, van Zoest, Jansen, & Roefs, 2022; Soetens, Braet, & Bosmans, 2008). This suggests that AB for food might not be always present. Possibly, characteristics of the task used to assess AB for food could influence how participants respond to the presented food images and thus indirectly influence AB for food. The current study used a task in which the distractor (i.e., the food stimuli) was completely irrelevant for correct task performance and was presented in peripheral vision. Irrelevant food distractor and response target shared no features and could never occur in the same location on the display. In contrast, in a dot-probe task or visual search task, as used in previous studies (e.g., Werthmann et al., 2016), food stimuli were presented centrally, and the location of a food image can coincide with the location of the crucial response target. The potential spatial overlap between food item and response target might create different AB dynamics than a scenario in which food image and response target share no features at all. However, specific design aspects of the current task might have been suboptimal, and this could have contributed to the current null findings. For example, the distractor was presented on 90% of the trials and therefore its occurrence was highly predictable thereby possibly rendering the task too easy. In this way, a potential AB for food might have gone unnoticed in the current version of the task.

Unexpectedly, we also did not observe any effects of mindset and dietary restraint, as well as no significant interactions between those factors on AB for food, even though the mindset manipulation was successful, as indicated by the manipulation check. This suggests that mindset might not be a crucial influence on AB for food. Also, increased AB for food might not be a crucial in explaining food craving in restrained eaters. This observation partly fits with results of a previous study that similarly did not observe effects of mindset and dietary restraint on eye-tracking based measures of AB for food (Werthmann et al., 2016). However, the current results are also partly at odds with results from this previous study because it detected an interaction between mindset and dietary restraint on response latency-based AB for food similarly. It was observed that restrained eaters show less AB to food when in a health mindset than when in a hedonic mindset. So, it could be that the current mindset manipulation or the current paradigm was not strong enough to affect AB for food as reflected in eye-movements.

Previously, mindset was manipulated by having the participant design a menu for different purposes. That is, either with the purpose of a festive event or with the purpose of helping a friend on a diet (Werthmann et al., 2016). In this way, the participant was actively involved in the manipulation. In the current study, mindset was manipulated by having the participant watch movies suggestive of a general atmosphere of the mindset condition. However, these movies were rather short (approx. 1 minute) and were only shown twice during the study (once just before the start of the AB task, and once in the middle of the task). So, the manipulation was rather short and involved no active contribution of the participant (though, the manipulation was effective according to the manipulation check). The active involvement of the participant in the mindset manipulation of the previous study may have yielded a stronger manipulation than the passive manipulation with video clips used in the current thesis. So, either the hypothesized effects of mindset might not exist, or the current mindset manipulation might not have been sufficient to set a long-lasting mindset in participants that would have been able to influence attention orienting during an AB task. So, it could be that a stronger manipulation is required to detect effects of mindset on eye-tracking based measures of AB for food. It seems that it is important that the participant plays an active role in the mindset manipulation for it to influence AB for food (Roefs et al., 2018).

In chapter 4, we assessed effects of dietary restraint and hunger on manual response latency-based AB for high-caloric and low-caloric food. We employed a visual search task that could distinguish between biased detection of food and distraction by food. We observed that participants with high levels of dietary restraint were faster especially at detecting low-caloric food than participants with low levels of dietary restraint. This suggests that dietary restraint particularly influences attention for low-caloric food, possibly because the chronic intention to diet increases the salience of particularly this type of food. However, this finding conflicts with results from a previous study, which observed that restrained eaters showed faster detection of high-caloric food than unrestrained eaters (Hollitt, Kemps, Tiggemann, Smeets, & Mills, 2010). Yet, Hollitt et al. (2010) did not present low-caloric food and the observed differences were mainly driven by longer response latencies to neutral targets in restrained eaters. So, it is currently unclear if restrained eaters show faster detection of high-caloric or low-caloric food.

In addition, we observed that participants with low levels of dietary restraint tended to be more distracted by both types of food than participants with high levels of dietary restraint. This finding suggests that restrained eaters are less sensitive to food than unrestrained eaters. Though unexpected, this finding fits with results from a previous study that also did not find evidence for increased distraction by food in restrained eaters (Hollitt et al., 2010). This finding might be explained retrospectively by the dieting intentions of restrained eaters. By chronically intending to restrict food intake, restrained eaters will likely learn to ignore food stimuli, and this may lead to the reduced distraction by food in restrained eaters that has been observed in the current thesis. So, restrained eaters might employ cognitive strategies to suppress attention orienting to food and thereby display less distraction by food (Blechert, Feige, Hajcak, & Tuschen-Caffier, 2010; Nederkoorn & Jansen, 2002; Piacentini, Schell, & Vanderweele, 1993). Therefore, it seems that restrained eaters are not generally more attracted by high-caloric food than unrestrained eaters. This study adds to the pool of studies that did not detect increased AB for food in restrained eaters (e.g., Ahern, Field, Yokum, Bohon, & Stice, 2010; Boon, Vogelzang, & Jansen, 2000; Johansson, Ghaderi, & Andersson, 2005; Werthmann et al., 2013; Wilson & Wallis, 2013). Overall, the inconsistent pattern of results across studies suggests that AB for food might not be a crucial phenomenon characterizing dietary restraint and might not play a critical role in explaining eating behavior of restrained eaters.

Against our expectations, we observed no effect of hunger on AB for food, suggesting that hunger might not be crucial for AB for food. This finding is not in line with some previous research (e.g., Castellanos et al., 2009; Jonker, Bennik, de Lang, & de Jong, 2020; Mogg, Bradley, Hyare, & Lee, 1998; Nijs, Muris, Euser, & Franken, 2010; Piech, Pastorino, & Zald, 2010; Sawada, Sato, Minemoto, & Fushiki, 2019; Stockburger, Schmälzle, Flaisch, Bublatzky, & Schupp, 2009; Hardman et al., 2021). However, effects of hunger are not found consistently in all studies (e.g., Ruddock, Field, Jones, & Hardman, 2018). Results from the current study suggest that hunger does not increase salience of food. We can only speculate why we did not detect effects of hunger on AB for food. Possibly, the current task was too abstract to capture effects of hunger on AB for food, because search displays consisted of written words which might be less appealing than pictorial food stimuli (however, see Freijy, Mullan, & Sharpe, 2014). Possibly, effects of hunger are more apparent on direct measures of AB, like eye-tracking (Hardman et al., 2021). So, the current study might have not been able to observe effects on hunger on AB due to the indirect response latency-based measurement of AB which was used. In addition, we observed no interaction between hunger and dietary restraint. Yet, the current results suggest that effects of hunger on AB for food do not differ between restrained and unrestrained eaters. This suggests that hunger might not be a crucial factor in triggering AB for food in restrained eaters (as well as in general).

Overall, the current results provide no evidence for differences in AB for (especially high-caloric) food between restrained eaters and unrestrained eaters. This result fits with part of the inconsistent literature on the topic (e.g., Ahern et al., 2010; Boon et al., 2000; Johansson et al., 2005; Werthmann et al., 2013; Wilson & Wallis, 2013) but contradicts other studies (e.g., Forestell, Lau, Gyurovski, Dickter, & Haque, 2012; Hepworth, Mogg, Brignell, & Bradley, 2010; Meule, Vogele, & Kubler, 2012; Neimeijer, de Jong, & Roefs, 2013). Results of the current studies on AB for food suggest that neither hunger nor mindset are influential factors on AB for food. However, previous studies did show that other state factors, like mood and metabolic state, influence AB for food, whereas trait factors, like dietary restraint or BMI, did not influence AB for food (Donofry et al., 2019; Stamataki, Elliott, McKie, & McLaughlin, 2019). That is, when considering effects of dietary restraint and mood on AB for food, only significant effects of mood were detected but no effects of dietary restraint and also no interaction between dietary restraint and mood (Donofry et al., 2019). Similarly, when assessing effects of BMI and metabolic state on AB for food, only effects of metabolic state were detected, but no effects of BMI and no interaction between BMI and metabolic state (Stamataki et al., 2019). Given the inconsistent findings, it appears that AB for food is a fluctuating and instable construct.

Food intake

Effects of dietary restraint, mindset, and hunger on food intake were assessed in chapters 3 and 4 of this thesis. In chapter 3, we assessed effects of dietary restraint and mindset on intake of high-caloric food during a bogus taste test. We did not observe any significant effects of mindset on food intake, suggesting that mindset may not influence food intake. This finding was unexpected and not in line with findings of other studies (Franssen et al., 2022; Pimpini et al., 2022). Pimpini et al. (2022) induced mindset (health vs. hedonic) with a within-subject manipulation and observed increased food intake in a hedonic compared to a health mindset, but only when the hedonic mindset was induced in the second session. This suggests that effects of mindset might be sensitive to context cues, and might not have been observed in the current study due to inhibitive effects of the laboratory environment on food intake, as the current study used a between-subjects mindset manipulation with only one session per participant (food neophobia effect; Guerrieri et al., 2007; Overduin & Jansen, 1997; Roefs & Jansen, 2004). Franssen et al. (2022) conceptualized mindset as control vs. loss of control mindset and assessed chocolate intake in chocolate lovers. Thus the taste test food was highly attractive for the participants, whereas we presented generally liked snack foods in the current study but did not consider if participants actually liked the foods. In addition, mindsets were conceptualized slightly differently, in that the current study induced a health mindset, with focus on healthy food and exercise, and a hedonic mindset, with focus on palatable food and food enjoyment. Theoretically, differences in conceptualization of the mindset as well as differences in participant characteristics (e.g., chocolate lovers vs. restrained/unrestrained eaters) could underlie the discrepant findings.

We observed a trend-level effect of dietary restraint on food intake, such that food intake was increased with increasing level of dietary restraint. This finding was unexpected, because restrained eaters have been observed to consume less food than unrestrained eaters when no breach of diet was imposed, or other disinhibiting stimulus was present (e.g., Herman & Mack, 1975; Hibscher & Herman, 1977; van Strien, Herman, Engels, Larsen, & van Leeuwe, 2007; Weber, Klesges, & Klesges, 1988). However, the current findings suggest that restrained eaters could be generally susceptible to overeating, even though they do not seem to display an increased AB for food. This idea fits with the finding that restrained eaters often have a higher BMI than unrestrained eaters (Ramírez-Contreras, Farrán-Codina, Izquierdo-Pulido, & Zerón-Rugerio, 2021). Alternatively, it could be that food stimuli in a cognitive task might be sufficient to disinhibit restrained eaters. So, increased intake could be related to disinhibition of restrained eaters by being exposed to high-caloric food items during the AB task. This interpretation would fit with previous studies showing that subtle food cues suffice to disinhibit restrained eaters to increase their food intake (Fedoroff, Polivy, & Herman, 2003; Jansen & Van den Hout, 1991; Polivy & Herman, 2017). However, since the current findings were only trend-level significant, one cannot base any solid conclusions on the current data.

In chapter 4, we tested effects of dietary restraint and hunger on intake of high-caloric and low-caloric food during a bogus taste test. We observed that participants consumed more calories from high-caloric than from low-caloric food. After removing one outlier, we observed that participants consumed significantly more calories from high-caloric food when fasted than when satiated, whereas there was no significant difference between calories consumed from low-caloric food between fasted and satiated states. So, hungry participants prefer high-caloric food as this type of food will refill energy stores more quickly.

In addition, we observed that participants with higher dietary restraint scores tended to consume more kilocalories specifically in a satiated state. This suggests that hunger is not a disinhibiting factor for restrained eaters. It rather suggests that satiety could have disinhibiting effects on restrained eaters. Possibly, satiation could trigger feelings of diet failure in restrained eaters, which could result in increased food intake. Alternatively, food intake could be increased in everyone in a hungry state, and effects of dietary restraint might only become apparent in a satiated state. However, the observed effect in this study has only been a trend, so we cannot draw strong conclusions from it. It is likely that other factors than hunger play a role in the dysregulation of eating behavior by restrained eaters.

We observed similar trends of dietary restraint on food intake in chapters 3 and 4. That is, in both chapters restrained eaters tended to consume more food than unrestrained eaters. This could indicate that dietary restraint encompasses people who generally tend to overeat. Potentially, these findings could supplement the literature on counterregulatory eating (e.g., Herman & Mack, 1975; Hibscher & Herman, 1977; van Strien et al., 2007; Weber et al., 1988), in which it has been shown that restrained eaters increase food intake after a preload, whereas unrestrained eaters decrease their intake after a preload, by showing that disinhibition could occur very easily in restrained eaters. Possibly, seeing pictures of food or feeling full might already suffice to disinhibit restrained eaters, as evidenced by a trend towards increased consumption in the taste tests conducted in the present thesis. This also fits with studies showing that the smell of food already is sufficient to disinhibit restrained eaters to increase their consumption in a taste test (Fedoroff et al., 2003; Jansen & Van den Hout, 1991; Polivy & Herman, 2017). However, since the observed effects were only trends, we cannot base any solid conclusions on them.

In chapter 3, we observed a positive trend-level correlation between food intake and manual response-latency based AB for food in the hedonic mindset, indicating that greater levels of AB for food are related to greater food intake, but only when it is relevant under the current mindset of a person. In chapter 4, we observed that AB for food correlated significantly with intake of low-caloric food but not with intake of high-caloric food. This also indicates that AB for food is related to food intake, under certain circumstances. These observations fit with results of a recent meta-analysis (Hardman et al., 2021), which revealed an association between AB for food and food intake. So, it could be that AB for food is an indicator of food related motivation and might be predictive of food intake. Because we only observed a significant correlation between AB for food and food intake in the hedonic mindset in chapter 3, it might be that AB for food is only indicative of food intake when food intake fits with people's intentions.

State vs. trait

The current results suggest that dietary restraint is related to increased food intake but not to increased AB for food or altered brain responses to food. So, the cognitive processing of food is rather influenced by the current state of a person, that is most likely by the current attentional focus. In some previous studies, it has been assumed that food is more attractive for restrained eaters than for unrestrained eaters (e.g., Burger & Stice, 2011;

Wang et al., 2016). When a heighted level of brain activity in response to food or an increased AB for food is expected in restrained eaters, a constant focus on hedonic aspects is assumed, but this assumption has rarely been tested and might not be true. Instead, restrained eaters might have the tendency to switch focus between hedonic and health related aspects of food while unrestrained eaters might have a more balanced perspective on food, therefore making them less likely to under- or overeat. So, it is conceivable that disinhibiting stimuli for restrained eaters, such as the smell of food or a pre-load, could work by focusing restrained eaters' attention on hedonic aspects of high-caloric food, whereas in other situations, when no disinhibiting stimulus is present, restrained eaters might be biased towards focusing on health-related aspects of food that emphasize their dieting goal, as the dieting state might be the default mental setting in the absence of a disinhibiting stimulus (see also Stroebe, Mensink, Aarts, Schut, & Kruglanski, 2008; Stroebe, Van Koningsbruggen, Papies, & Aarts, 2013).

Furthermore, restrained eaters are comprised of a rather heterogeneous group of individuals. For example, some restrained eaters may be successful at dieting whereas others may be unsuccessful at dieting. Which type of restrained eater is detected may depend on the scale used to measure dietary restraint (Adams, Chambers, & Lawrence, 2019; Mills, Weinheimer, Polivy, & Herman, 2018). Possibly, dieting motivation and approach might not be the same for all restrained eaters, and also dieting history might differ between restrained eaters (Mills et al., 2018). The heterogeneity in the construct of dietary restraint may complicate finding consistent relationships between dietary restraint and cognitive measures such as AB for food and brain responses to food (Watson & Le Pelley, 2021). So, a further refinement in the definition of dietary restraint might be needed to be able to observe consistent relations between dietary restraint and cognitive measures if they exist at all. It might be insightful to further identify subtypes of dieters which could potentially show idiosyncratic patterns in AB for food and brain responses to food.

Conclusions & future research

The following main conclusions can be drawn from the current thesis:

- The level of brain activity did not reflect the palatability and barely reflected the calorie content of food items. So, the level of brain activity does not correspond to the reward value of food. Instead, it was strongly influenced by attentional focus, with many brain regions of the mesocorticolimbic system showing the highest activity level in the hedonic attentional focus, indicating that the level of brain activity rather reflects the salience of food. This suggests that the theory proposing that an increased brain activity level in response to food corresponds to increased reward value of food is deficient, because this theory logically requires observing differences in brain activity level between palatable and unpalatable food stimuli.
- Palatability and calorie content of food were reflected in multi-voxel patterns of brain activity. So, the current thesis suggests that MVPA is required to study how food characteristics are represented the brain.
- Brain responses to food were not related to dietary restraint. Instead, the current attentional focus influenced strongly how the brain responded to food stimuli. This suggests that the current mental state is much more influential in determining how the brain responds than a more stable behavioral trait. Potentially, effects of dietary restraint and attentional focus have been confounded in previous literature, because attentional focus has rarely been measured or controlled.
- Dietary restraint was not related to an increased AB for (high-caloric) food. Given the overall inconsistent results in the literature, combined with the current null findings, AB for food might not be the most promising research avenue to explain food craving in restrained eaters. Possibly, other mechanisms underlie the conflicted food approach of restrained eaters.
- Neither mindset nor hunger significantly affected AB for food. So, the explanatory power of these factors might be limited.

- Mindset is difficult to manipulate. Possibly, an effective mindset manipulation might need to be tied to the experimental task that the participant performs and might need to build on active involvement of the participant in the manipulation.

Future research may devise a more effective mindset manipulation. Possibly, an effective mindset manipulation will require active involvement of the participant and will ideally be embedded in the experimental task. Perhaps, future research could make use of virtual reality (VR) to create an involving and realistic mindset manipulation. In addition, future research might test the effect of more nuanced mindsets which will likely resemble spontaneous mindsets of participants more closely and might also consider effects of mindset that has been induced over a longer period of time (e.g., in a VR game).

Future research might further investigate how reward value and motivational salience of food items are reflected in brain activity. One could devise more direct manipulation of food reward value and motivational salience, to test these effects more directly. One could do this for example by having participants directly rate how rewarding stimuli are or how motivated people are to eat/avoid a food, instead of tailoring stimuli based on palatability and calorie content.

In addition, future research could further investigate how different food characteristics are represented in the brain. To do this, it will be crucial to employ multivariate analysis techniques. Representational similarity analysis (RSA) might be employed to assess how the brain represents food in more detail. In RSA, representational dissimilarity matrices (RDMs) are created which organize a set of stimuli based on their (dis)similarities on a specific modality, like brain activity patterns, behavioral stimulus ratings, or objective stimulus properties. Then, by comparing the RDMs based on different modalities, the (dis)similarity structure can be compared between different modalities (e.g., neural dissimilarity structure and behavioral dissimilarity structure; Kriegeskorte, Mur, & Bandettini, 2008). In this way, one could compare the dissimilarity structure between brain response patterns to food and behavioral ratings of food, such as palatability or calorie content ratings, or objective food properties, like calorie content, macronutrient content, or micronutrient content. This would enable assessing which particular aspects of food characterize the representations of food in the brain.

To further investigate AB for food, future research could improve the paradigm that is used to measure AB. Future research might further test the suitability of the additional singleton paradigm to investigate AB for food with improved design, such as performing the task with a more balanced ratio between distractor present and distractor absent trials.

To clarify the role of dietary restraint, future research may need to characterize restrained eaters in more detail, and potentially create a more fine-grained subdivision of restrained eaters into different types, for example by creating different dieting profiles. In this way, one may be better able to explain the behavior of different types of dieters.

Taken together, to further advance understanding of brain responses to food it will be essential to have a clear mental task for the participants during scanning, to know the mental processes they engage in during scanning. Only in this way, one will be able to interpret the observed brain activity without having to rely on reverse inference (Poldrack, 2006, 2011). To further understand the role of AB for food in instantiating and maintaining craving in restrained eaters, one might need to devise better paradigms to assess AB for food and potential moderating variables. However, it currently seems that AB may not explain craving in restrained eaters and therefore may not be the way forward in understanding eating behavior in restrained eaters.

A

Appendix

Summary

Impact addendum

Curriculum vitae

Acknowledgement

References

Summary

Our current society is characterized by conflicting views on food. One the one hand, food enjoyment is viewed as highly desirable but on the other hand, a thin body shape is idealized. The modern food environment presents an overabundance of highly palatable, high-caloric, cheap, and easily accessible food (Hill & Peters, 1998; Morland & Evenson, 2009; Townshend & Lake, 2017). As a result, the prevalence of obesity is rapidly increasing (Berghofer et al., 2008; Flegal, Carroll, Ogden, & Curtin, 2010; WHO, 2020). This represents a problematic development, as obesity is associated with numerous detrimental health outcomes, such as diabetes and heart disease (Finkelstein, Ruhm, & Kosa, 2005; WHO, 2020). In this obesogenic environment, many people engage in chronic dietary restraint, that is, they constantly monitor their food intake to try to limit their food intake to control their body weight (Herman & Polivy, 1980). Restrained eaters might be particularly torn between the conflicting aspects of high-caloric palatable food (Stroebe, Van Koningsbruggen, Papies, & Aarts, 2013). The conflicting aspects of food are likely reflected in a person's mindset with respect to food (Werthmann, Jansen, & Roefs, 2016). People can be in a hedonic mindset, in which they likely focus on pleasure derived from food. Alternatively, people can be in a health mindset in which they likely focus on health-related aspects of food consumption. Restrained eaters might be particularly prone to fluctuate between these mindsets (Werthmann et al., 2016). However, food perception may generally be influenced by the current state of the individual. Also, other factors, like hunger, likely influence the way an individual reacts to food (cf., Hardman et al., 2021). The current thesis assessed effects of mindset and hunger (state factors) and dietary restraint (trait factor) on brain responses to food, attention bias (AB) for food and food intake.

Chapter 1 provides a general introduction to the topics of this dissertation. It discusses the inconsistent literature on brain responses to food in restrained eaters (Roefs, Franssen, & Jansen, 2018; Werthmann, Jansen, & Roefs, 2015). Furthermore, it highlights the double-sided nature of high-caloric food. That is, high-caloric food has a high hedonic value, because its consumption is pleasurable, but a low-health value, because it promotes weight gain. It proposes that considering the double-sided nature of high-caloric food by

taking mindset into account will help in resolving the inconsistencies (Roefs et al., 2018). In addition, this chapter discusses the inconsistent literature on AB for food in restrained eaters, and suggests that current states (mindset, hunger) play a role in AB for food, and need to be considered to resolve the inconsistencies. Finally, the aim and main hypotheses are introduced. In short, we expected that brain responses in the mesocorticolimbic system would be highest in response to high-caloric palatable food, particularly in a hedonic attentional focus. We expected that attentional focus dependent differences in brain responses to food would be most marked in participants with high levels of dietary restraint. Furthermore, we hypothesized that AB for food would be stronger and food intake would be higher in a hedonic than in a health mindset, and that effects of mindset would be most noticeably in participants with high levels of dietary restraint. In addition, we expected an increased AB for food in participants with high levels of dietary restraint, especially in a hungry state.

In chapter 2, we investigated if attentional focus and dietary restraint influence brain responses to foods that varied in both caloric content and palatability. To this end, we conducted a functional magnetic resonance imaging (fMRI) study in which female participants with varying levels of dietary restraint were presented with individually tailored palatable and unpalatable, high-caloric and low-caloric food pictures. In each participant, we induced three attentional foci (hedonic, health, and neutral) with a fast-paced one-back task. We analyzed the results using mass-univariate analysis techniques, in which a separate analysis at each voxel is conducted, and average brain activity level is assessed, as well as using multi-voxel pattern analysis (MVPA) in which patterns of brain activity across multiple voxels are assessed. We observed only small differences in activity level between high-caloric and low-caloric food. We also observed no differences in brain activity level between palatable and unpalatable food. These results were also supported by Bayesian analyses which showed mostly evidence in favor of the null hypothesis (no differences in brain activity level between palatable and unpalatable food stimuli; no differences in brain activity level between high-caloric and low-caloric food stimuli). Instead, brain activity level was strongly influenced by attentional focus. We observed 28 cluster with significantly different activity level between the three attentional foci. Most regions belonging to the mesocorticolimbic system, which is considered as the brains' reward system, responded most strongly in the hedonic attentional focus. Brain activity level did not depend on dietary restraint. Palatability and calorie content could be decoded using MVPA, but decoding performance did not depend on attentional focus and was not correlated with dietary restraint. These results suggest that the level of brain activity does not reflect the rewarding value of food, because brain activity level did not differ between palatable stimuli, which are highly rewarding, and unpalatable stimuli, which are not rewarding at all. Both, palatable and unpalatable food stimuli are highly salient (cf., Kahnt, 2018; Kahnt & Tobler, 2017), and food in general will be most salient when hedonic aspects are considered. So, the current results suggest that the level of brain activity could reflect the salience of food. This suggests that the theory, which states that increased brain activity level in response to food reflects the increased reward value of food is inaccurate, because this theory predicts differential activity levels between palatable and unpalatable food stimuli (cf., Roefs et al., 2018). Food characteristics, like palatable and calorie content, are not reflected in the level of brain activity but instead in multi-voxel patterns of brain activity.

In chapter 3, we investigated if mindset and dietary restraint affect AB for food and food intake. Therefore, we had female students with varying levels of dietary restraint perform a visual search task during which eye-movements and response latencies were recorded. In the visual search task, participants had to locate a target stimulus and indicate its identity while food and neutral distractors, which must be ignored, appeared on the display. Mindset was manipulated with short video clips that either portrayed appetizing food and people enjoying food to induce a hedonic mindset, or healthy food and people exercising to induce a health mindset. Food intake was measured during a bogus taste test, in which participants were required to taste different types of high-caloric snack foods and rate their taste, while the amount of food consumed was covertly measured. We observed that the neutral distractor tended to be fixated more often than the food distractor. So, if anything, participants focused their attention away from food. However, we observed no effects of mindset and dietary restraint on eye-movements or reaction times. Similarly, we observed no effects of mindset on food intake, but we observed that participants with higher dietary restraint scores tended to consume more food during the bogus taste test. We also observed that manual response latency-based AB for food and food intake tended to correlate positively, but only in the hedonic mindset. So, the current results suggest that restrained eaters are not characterized by an increased AB for food, but that they might be more prone to overconsumption of food, nonetheless.

In chapter 4, we assessed if hunger and dietary restraint influence AB for food and food intake. To this end, we recruited female restrained eaters and asked them to perform a visual search task, in which we measured reaction times. During the visual search task, participants were presented with matrices consisting of words. Matrices either consisted of neutral words with one food words, or food words with one neutral word. Food intake was assessed during a bogus taste test, in which participants were asked to taste and rate high-caloric and low-caloric snack foods, while we secretly measured how much food participants consumed. In the visual search task, we observed that participants with high levels of dietary restraint were faster especially at detecting low-caloric food than participants with low levels of dietary restraint. Participants with low levels of dietary restraint were generally more distracted by food than participants with high levels of dietary restraint. During the taste test, we observed that participants consumed more calories from high-caloric food when fasted than when satiated, whereas there was no significant difference in calories consumed from low-caloric food between fasted and satiated states. In addition, participants with high levels of dietary restraint tended to consume more food when satiated. AB for food tended to correlate with intake of low-caloric food. These results also suggest that restrained eaters are not characterized by an AB for food, but might have the tendency to overeat.

Chapter 5 provides a summary and discussion of the main findings and conclusions of the current dissertation and presented suggestions for future research. In brief, the results of the current thesis suggest that the level of brain activity does not reflect palatability and barely reflects calorie content of food. This indicates that the level of brain activity does not reflect the reward value of food. Instead, the level of brain activity was strongly influenced by attentional focus, with the highest level of brain activity being detected in the hedonic attentional focus, in which food is likely highly salient. So, it seems that the level of brain activity in response to food reflects motivational salience instead of reward value of food. This suggests that dominant theory, which suggests that increased level of brain activity in the mesocorticolimbic system in response to food reflects the reward value of food, is flawed, because this theory predicts differences in brain activity level highly palatable and unpalatable food stimuli (cf., Roefs et al., 2018). Instead, palatability and calorie content of food items are reflected in multi-voxel patterns of brain activity. Brain responses to food were also not related to dietary restraint, suggesting that the current mental state is more influential on brain responses to food. Effects of attentional focus might have gone unnoticed in previous studies, as attentional focus has rarely been considered. Furthermore, dietary restraint was not related to an increased AB for (high-caloric) food. Considering the overall inconsistent results in the literature (Werthmann et al., 2015), it seems that AB for food might not underlie craving in restrained eaters. One might need to investigate other factors to explain the conflicted food approach of restrained eaters. Also, mindset and hunger did not influence AB for food, and might be less influential on AB for food than expected. Altogether, the current results underline the importance of a clear mental task when studying brain responses to food, and suggest that AB for food is not a crucial factor in conflicted food motivation in restrained eaters.

A

Impact addendum

Main findings

The aim of the current dissertation was to assess the effects of mindset, hunger, and dietary restraint brain responses to food and on attention bias (AB) for food, to better understand mechanisms behind dietary restraint. We observed that the level of brain activity in response to food stimuli does not depend on palatability or calorie content. So, the level of brain activity does not distinguish between highly palatable stimuli, which are rewarding, and highly unpalatable stimuli, which are not rewarding. Therefore, it is unlikely that the level of brain activity reflects the rewarding value of food. Instead, the level of brain activity is strongly influenced by the attentional focus of a person, with highest activity when people focus on hedonic aspects of food. So, attentional focus is crucial in determining how the brain responds to food. It is likely that food is most salient in the hedonic mindset. Therefore, the findings suggest that the level of brain activity reflects salience rather than reward value. Palatability and calorie content are reflected in multi-voxel patterns of brain activity, suggesting that the brain stores information about food characteristics in a distributed fashion. Also, brain responses to food were not related to dietary restraint. So, food does not appear to be more salient for restrained eaters. In addition, we observed no evidence for an increased AB for food in restrained eaters. Neither mindset nor hunger influenced AB for food in the current thesis. These findings suggest that AB for food might not be a crucial factor determining behavior in restrained eaters.

Relevance

In todays' society, millions of people suffer from obesity and associated health problems (WHO, 2020). Dietary restraint has been associated with weight gain and obesity (Ramírez-Contreras, Farrán-Codina, Izquierdo-Pulido, & Zerón-Rugerio, 2021; Snoek, van Strien, Janssens, & Engels, 2008). Therefore, a better understanding of the mechanisms underlying dietary restraint could help in preventing the onset of obesity and the treatment of obesity. The current thesis contributes to further understanding mechanisms underlying dietary restraint.

A dominant view in the literature proposes that levels of brain activity in response to food are increased in people with obesity and restrained eaters, which are interpreted as reflecting increased rewarding value of food in these groups. However, also the results on this proposal are inconsistent (Roefs, Franssen, & Jansen, 2018). The current thesis shows that attentional focus crucially influences the level of brain activity, but that the level of brain activity is not influenced by palatability, calorie content, or dietary restraint. The current results thus provide new insights into the field and suggest that previous approaches, which propose that increased brain activity levels in response to food are a characteristic of people with obesity and restrained eaters, have been too simplistic. Instead, the current findings show that brain responses to food are not a stable characteristic of a person but that the way one looks at food determines how the brain reacts to it. So, the current state of a person needs to be considered when assessing brain responses to food. The current thesis shows that attentional focus is relevant for daily food decisions. Possibly, prevention strategies or even intervention methods for obesity could target the attentional focus, to make people look at food from a health perspective, to influence food decision making in a healthy direction.

Previous research has proposed that an AB for food could be a mechanism underlying altered food approach behavior in restrained eaters. However, evidence for this idea is mixed (Roefs, Houben, & Werthmann, 2015; Werthmann, Jansen, & Roefs, 2015), with studies observing increased AB for food in restrained eaters (Brooks, Prince, Stahl, Campbell, & Treasure, 2011; Dobson & Dozois, 2004; Forestell, Lau, Gyurovski, Dickter, & Haque, 2012; Hepworth, Mogg, Brignell, & Bradley, 2010; Meule, Vogele, & Kubler, 2012; Neimeijer, de Jong, & Roefs, 2013) decreased AB for food in restrained eaters (Hotham, Sharma, & Hamilton-West, 2012), or no difference in AB for food between restrained and unrestrained eaters (Ahern, Field, Yokum, Bohon, & Stice, 2010; Boon, Vogelzang, & Jansen, 2000; Johansson, Ghaderi, & Andersson, 2005; Werthmann et al., 2013; Wilson & Wallis, 2013). The current thesis attempted to clarify the role of AB for food in dietary restraint by assessing it in combination with state factors that were expected to have moderating effects on AB for food. The results of this thesis show that people scoring high on dietary restraint are not characterized by increased AB for food. Considering the highly inconsistent literature, with many studies observing no increased AB for food in restrained eaters, this suggests that increased AB for food is not a crucial mechanism underlying dietary restraint. Future research might better focus on other potential mechanisms to gain a better understanding of dietary restraint. Furthermore, interventions using AB modification training, in which attention is directed away from food, might not be useful for changing food approach behavior in restrained eaters, as increased attention for food is most likely not crucial in restrained eating.

Target groups

The current thesis examined predominantly healthy-weight college-aged females, which were categorized according to their level of dietary restraint. Therefore, this thesis is of interest to researchers who study eating behavior or who are interested in factors that lead to obesity. In addition, this thesis is of interest to dieticians and clinicians who want to deepen their understanding of processes underlying obesity. In the broadest sense, this thesis is of interest to anyone who wants to gain a deeper insight in factors motivating food-related cognition is generated by the current studies. Furthermore, this thesis is of interest to neuroscientists using fMRI because our findings demonstrate the importance of a well-controlled mental task for the interpretability of fMRI results. In addition, our results show that information about value cannot be derived from the level of brain activity but only from patterns of brain activity.

Activities

The current dissertation contributes to a better understanding of restrained eating and puts the theory on reward-related brain responses to food in a new perspective. The studies of this dissertation have been presented at conferences and will be published in scientific journals. The insights provided by the current dissertation could be useful in aiding the development of new prevention and invention methods for obesity. The current results suggest that it might be beneficial to target the attentional focus of person in future behavioral interventions. This may be implemented with ecological momentary assessment, so that the mindset of people can be targeted in daily life.

Curriculum Vitae

Sarah Kochs was born on August 29th, 1990, in Geilenkirchen (Germany). She graduated from secondary school (Bischöfliches Gymnasium St. Ursula, Geilenkirchen, Germany) in July 2011. From September 2011 - July 2014 she studied Psychology at Maastricht University (The Netherlands) and obtained a Bachelor of Science degree in Psychology. She worked as student tutor from 2013-2014. From September 2014 – August 2016 she was enrolled in the Research Master in Cognitive and Clinical Neuroscience with specialization in Cognitive Neuroscience at Maastricht University and obtained a Master of Science Degree in Cognitive and Clinical Neuroscience. She worked as research assistant collecting data for a behavioral study on the role of time intervals in associative memory (October 2014 – April 2015). In addition, she completed an internship (February – August 2016) at Maastricht University during which fMRI was used to study neural processing of time intervals in associative memory. In October 2016, she started a PhD project at the Eating Disorders and Obesity Research Group at the department of Clinical Psychological Science at Maastricht University supervised by supervised by Prof. dr. Anne Roefs and Prof. dr. Anita Jansen. In this project she investigated effects of mindset, hunger, and dietary restraint on attention bias for food and brain responses to food.

Publications

Pimpini, L., Kochs, S., van Zoest, W., Jansen, A., & Roefs, A. (2022). Food captures attention, but not the eyes: An eye-tracking study on mindset and BMI's impact on attentional capture by high-caloric visual food stimuli. *Journal of Cognition, 5*(1). https://doi.org/10.5334/joc.210

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Submitted work

Kochs, S., de Vos, M., Havermans, R.C., Jansen, A., & Roefs, A. (2022). If anything, dietary restraint is associated with reduced distraction by food. *Submitted manuscript.*

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Kochs, S., Franssen, S., Pimpini, L., van den Hurk, J., Valente, G., Roebroeck, A., Jansen, A., & Roefs, A. (2021). It is a matter of perspective: attentional focus rather than dietary restraint drives brain responses to food stimuli. *Submitted manuscript.*

Conference presentations

Kochs, S., Pimpini, L., Franssen, S., van den Hurk, J., Jansen, A., & Roefs, A. (2021, July 12 – 15). *It is a matter of perspective: attentional focus rather than dietary restraint drives neural responding to food stimuli* [Poster presentation]. 28th Annual Meeting of the Society for the Study of Ingestive Behavior, Online event.

Kochs, S., Pimpini, L., Franssen, S., van den Hurk, J., Jansen, A., & Roefs, A. (2021, March 31 – April 1). *It is a question of perspective: attentional focus rather than dietary restraint drives neural responding to food cues* [Conference presentation]. The British Feeding and Drinking Group (BFDG) 45th Annual Meeting, Online event.

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