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Independent functional connectivity networks underpin food and monetary reward sensitivity in excess weight

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ABSTRACT

Overvaluation of palatable food is a primary driver of obesity, and is associated with brain regions of the reward system. However, it remains unclear if this network is specialized in food reward, or generally involved in reward processing. We used functional magnetic resonance imaging (fMRI) to characterize functional connectivity during processing of food and monetary rewards. Thirty-nine adults with excess weight and 37 adults with normal weight performed the Willingness to Pay for Food task and the Monetary Incentive Delay task in the fMRI scanner. A data-driven graph approach was applied to compare whole-brain, task-related functional connectivity between groups. Excess weight was associated with decreased functional connectivity during the processing of food rewards in a network involving primarily frontal and striatal areas, and increased functional connectivity during the processing of monetary rewards in a network involving principally frontal and parietal areas. These two networks were topologically and anatomically distinct, and were independently associated with BMI. The processing of food and monetary rewards involve segregated neural networks, and both are altered in individuals with excess weight.

Introduction

Obesity is one of the most important health problems in developed countries, as it is linked to leading causes of mortality (e.g., cardiovascular disease, diabetes) (Flegal et al., 2013). In recent decades, the prevalence of obesity has reached worldwide epidemic proportions (Ng et al., 2014) and this growth has been linked to the availability of highly processed food rich in sugar and fat (Stice et al., 2013). Obesity is increasingly conceptualized as a disorder of reward-based decision-making, according to cognitive neuroscience evidence showing that obese people predominantly make food choices based on the rewarding aspects of food products, instead of their homeostatic or health properties (Burger and Stice 2011; Kenny 2011; Volkow et al., 2011).

Value-based choices rely on the function of a well-defined network of brain regions central to reward processing, including the anterior cingulate, orbitofrontal and dorsal prefrontal cortices, the ventral striatum, the midbrain and the amygdala (Haber and Knutson 2009). Individuals with excess weight show significantly increased activation in these areas in response to high caloric food cues (Dimitropoulos et al., 2012; Martin et al., 2010; Rothemund et al., 2007; Simon et al., 2014; Stoeckel et al., 2008). However, despite evidence that these reward-related regions behave as an integrated network, it is as yet unclear how network-level disturbances relate to altered brain reward processing in obesity. Functional connectivity studies have examined discrete elements of the brain's reward-processing system (e.g., prefrontal cortex, striatum), but these studies have reported contradictory findings. While some studies in excess weight adults have found enhanced functional connectivity of prefrontal and striatal areas during processing of highly palatable food (Carnell et al., 2014; Kullmann et al., 2013; Nummenmaa et al., 2012; Stoeckel et al., 2009) other studies found reduced functional connectivity in prefrontal areas (García-García et al., 2013).

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In addition, it remains unclear whether disruptions of the neural systems supporting reward-based decision-making in this population are specific to the processing of food-related stimuli or represent a general sensitization of reward processes. The existence of a general deficit of reward-processing, (i.e., independent of the specific stimulus), predicts that obese people will have generic problems in evaluating natural reinforcers, which, in turn, may have a broad impact on day-to-day choices and hence physical and mental health (Rangel 2013). Nevertheless, few studies have examined the brain's reward system activity in excess weight individuals during the processing of generic stimuli, such as monetary reward. Balodis et al. (2013) found increased activity in the ventral striatum and ventromedial prefrontal cortex in anticipation of monetary reward. This is consistent with evidence of altered structural connectivity in fronto-striatal circuits in obese individuals, and implies a general reward-processing deficit (Marqués-Iturria et al., 2015). However, other studies have failed to find an association between brain monetary processing and body mass index (BMI) (Simon et al., 2015). These inconsistencies underscore the need for a comprehensive characterization of the functional connectivity of the reward network in excess weight adults across food-related and other types of stimuli.

We used functional magnetic resonance imaging (fMRI) to map brain functional connectivity alterations in the reward system of individuals with excess weight relative to normal weight controls. Both groups performed two tasks: one assessing the processing of food-related rewards and one assessing the processing of monetary rewards. Functional connectivity was assessed with a data-driven graph theoretic approach to characterize whole brain network-level between-group differences in both tasks. Based on prior work (Nummenmaa et al., 2012; Stoeckel et al., 2009), we hypothesized that excess weight individuals would show disrupted functional connectivity in frontal and striatal regions. If excess weight individuals show a general reward-processing deficit, then these disruptions should also be evident during the processing of monetary reward. Finally, we predicted that these network-level functional connectivity disruptions would be associated with behavioral measures of sensitivity to reward and physical measures of adiposity.

Materials and methods

Participants

Seventy-six right-handed adults, aged between 25 and 45 years old were classified in two groups according to the criteria of the World Health Organization to define excess weight (=overweight or obesity). The groups were comprised of 39 participants with excess weight (BMI > 25) and 37 participants with normal weight (controls). The groups did not differ significantly in terms of age ($t_{(1,74)}$=−0.40, p=0.69), sex ($t_{(1,74)}$=−0.02, p=0.99), years of education ($t_{(1,74)}$=0.72, p=0.47), or monthly income ($t_{(1,74)}$=−0.63, p=0.39) (Table 1).

Participants were recruited through general hospitals and media advertisements. The exclusion criteria were: (i) history or current evidence of neurological or psychiatric disorders, including substance use disorders, indicated by semi-structured interviews conducted by Masters-level professional psychologists; (ii) medical comorbidities associated with obesity (e.g., diabetes, hypertension); (iii) significant abnormalities on structural MRI or any contraindications to MRI scanning. All participants had normal or corrected-to-normal vision. The study was approved by the Human Research Ethics Committee of the University of Granada. All participants signed an informed consent form and received a 50€ compensation for their time commitment in the study.

Experimental paradigm

Each participant performed two tasks during the fMRI session, a monetary reward task (Monetary Incentive Delay task) and a food-related reward task (Willingness to Pay task). To ensure that participants were familiar with the food stimuli used in the Willingness to Pay task, participants attended a tasting session two weeks before scanning. During this session participants tasted the 18 foods that we would later present, as visual stimuli, in the task. These foods belonged to two groups, defined a priori by the research team, based on their degree of palatability: highly palatable food, including sweet and fatty food (e.g., chocolate, cheese cake, burger) versus plain food (e.g., yoghurt, omelet). The tasting session had two aims. The first was to ensure that all participants had tried the food stimuli that we would subsequently present in the scanner. The second aim was to collect subjective ratings of “liking” after tasting the actual foods, and thus to validate the categories that we had established “a priori” i.e. to check that highly palatable foods were more “liked” than plain foods. All tasting sessions were conducted at 6:00 p.m., and participants were instructed to taste each of the foods offered and to rate how much they liked them using a 1–10 scale. Both groups showed higher “liking” rating for highly palatable compared to plain food (all p < 0.05), validating our prior classification.

Table 1
Sociodemographic characteristic and body composition by group.

	Normal weight (n=37) Mean (SD)	Excess weight (n=39) Mean (SD)
Age	33.00 (6.53)	33.59 (6.23)
Sex (male/female)	17 / 20	18 / 21
Years of education	18.35 (3.71)	17.74 (3.65)
Monthly income		
< 600€	21.6%	10.3%
601–1000€	10.8%	10.3%
1001–1500€	18.9%	28.2%
1501–2000€	16.2%	12.8%
2001–2499€	10.8%	17.9%
> 2500€	21.6%	17.9%
BMI (kg/m^2)	22.28 (1.77)	30.41 (3.69)
Fat (%)	19.71 (6.07)	30.99 (8.65)

SD, Standard Deviation; BMI, Body mass index.

BMI and fat percentage were obtained before the fMRI scan using a body composition analyzer TANITA BC-420 (GP Supplies Ltd., London, UK). During the fMRI session, to control the potential effects of hunger/satiety levels, participants rated their appetite using a 10-cm visual analogue scale (VAS) three times along the fMRI session: prior to scan, immediately before the food-stimuli task and immediately after leaving the MRI room.

fMRI tasks

Willingness to Pay task (WtP)

We used a modified version of the Willingness to pay task (Plassmann et al., 2007). Participants were presented with a picture of each of the 18 foods previously tasted. All pictures were shot ad hoc for the study, using standardized presentation and lightning conditions. Therefore, all images were matched for visual properties and serving size. Highly palatable and plain food naturally differed in caloric content based on nutrition facts, although we did not code or analyzed this variable quantitatively. Each stimulus was presented once for two seconds followed by a four-second response period, during which time participants answered the question: “How much would you pay for it?” They could choose between four monetary options, ranging from 20 cents to 10 euros. Each selection was followed by a variable fixation period lasting between 3 and 5 seconds. Our goal in this task was to examine brain activity and functional connectivity in high palatable food trials compared to plain food trials.

Monetary Incentive Delay task (MID) (Knutson et al., 2000 Nestor et al., 2010)

In each trial, participants were shown one of two cues (green or