Published in final edited form as:

Psychol Sci. 2013 November 1; 24(11): 2262–2271. doi:10.1177/0956797613492985.

Self-Regulatory Depletion Enhances Neural Responses to Rewards and Impairs Top-Down Control

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Abstract

To be successful at self-regulation, individuals must be able to resist impulses and desires. The strength model of self-regulation suggests that when self-regulatory capacity is depleted, self-control deficits result from a failure to engage top-down control mechanisms. Using functional neuroimaging, we examined changes in brain activity in response to viewing desirable foods among thirty-one chronic dieters, half of whom underwent self-regulatory depletion using a sequential task paradigm. Compared to non-depleted dieters, depleted dieters exhibited greater food cue-related activity in the orbitofrontal cortex, a brain area associated with coding the reward value and liking aspects of desirable foods and also showed decreased functional connectivity between this area and the inferior frontal gyrus, a region commonly implicated in self-control. These findings suggest that self-regulatory depletion provokes self-control failure by reducing connectivity between brain regions involved in cognitive control and those representing rewards thereby decreasing the capacity to resist temptations.

Keywords

Self-Regulation; Self-Control; Depletion; Reward; Food; Orbitofrontal Corte; fMRI

Failures of self-control are responsible for a wide variety of societal ills. Difficulty inhibiting urges and regulating desires lie at the root of such current health concerns as obesity and substance abuse. Contemporary models of self-regulation emphasize the role of a limited capacity resource that, when exhausted, increases the enactment of unwanted behaviors. For example, self-regulatory resource depletion leads dieters to break their diets and overeat (Hofmann, Rauch, & Gawronski, 2007; Vohs & Heatherton, 2000), smokers to smoke (Shmueli & Prochaska, 2009) and social drinkers to drink more than non-depleted individuals (Muraven, Collins, & Nienhaus, 2002). Since it was first formulated (e.g. Baumeister & Heatherton, 1996), the strength model has been supported by a wide array of studies both inside the laboratory (for a meta-analysis see Hagger, Wood, Stiff, & Chatzisarantis, 2010) and outside of it (e.g., Hofmann, Vohs, & Baumeister, 2012). Despite the wealth of evidence supporting this model of self-control, the precise mechanism by which successive acts of self-regulation can engender self-regulatory collapse is widely

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debated (Beedie & Lane, 2011; Inzlicht & Schmeichel, 2012; Job, Dweck, & Walton, 2010; Kurzban, 2010; Schmeichel, Harmon-Jones, & Harmon-Jones, 2010).

Recently, a number of studies have argued that current formulations of the strength model may overemphasize the role of weakened restraint and impaired control in self-regulation failures. For instance, Schmeichel and colleagues note that prior work showing increased consumption of pleasurable foods after depletion can be interpreted as evidence of weakened control, increased impulse strength, or a combination of both (Schmeichel et al., 2010). Indeed, they found that self-regulatory depletion improves, rather than interferes with, the ability to detect rewarding stimuli (Schmeichel et al., 2010). Likewise, Vohs and colleagues (Vohs et al., 2012) demonstrated that self-regulatory depletion increases the strength of desires and emotions in the absence of any demands to regulate behavior. For example, they showed that following depletion, participants rated pleasant images more favorably, found pain more intense, and, upon exposure to appetizing food, reported greater desires to consume the food items (Vohs et al., 2012). Together, these new findings suggest that self-regulatory depletion may act directly on desire strength, increasing the lure and pull of temptations thereby rendering them more difficult to inhibit.

How might self-regulatory depletion lead to an intensification of desires? One recent theory proposes that depletion interferes with the ability to monitor for situations and cues that conflict with goals, which in turn increases the likelihood that people will attend and respond to rewarding stimuli (Inzlicht & Schmeichel, 2012). Put differently, people often desire rewarding items and experiences (i.e., food, sex, or Facebook) but spend a considerable portion of their waking hours keeping these desires in check (see Hofmann et al., 2012). When the capacity to self-regulate is depleted, self-monitoring is reduced and motivation shifts towards gratification. Another mechanism, one which is not incompatible with the above theory, comes from a recent neural systems model of self-regulation failure proposed by Heatherton and Wagner (2011). In this “balance” model of self-regulation, ongoing self-control is sustained by a balance between brain regions involved in impulse control (i.e., lateral and medial regions of the prefrontal cortex) and brain areas involved in representing the reward value, desirability and emotional valence of a stimulus (e.g., the orbitofrontal cortex and striatum). According to this model, self-control fails when the strength of an impulse exceeds the capacity to regulate it, such as might occur during adolescence when frontal control is still developing (Somerville, Jones, & Casey, 2010). The model also suggests that impulse strength is under constant moderation from regions involved in top-down control; therefore any disruption of executive control can lead to increased impulse strength. According to this model, then, depletion operates by disrupting frontal control thereby releasing brain regions involved in representing the reward value of temptations.

In the current study we used functional neuroimaging in conjunction with a well validated food cue-reactivity task (i.e., Demos, Heatherton, & Kelley, 2012; Demos, Kelley, & Heatherton, 2011; Wagner et al., 2012) to examine two questions about how self-regulatory depletion disrupts brain mechanisms involved in self-control : 1) does self-regulatory depletion increase the reward value of a naturally rewarding stimulus such as high-calorie appetizing food? and 2) Does self-regulatory depletion interfere with top-down control

mechanisms which serve to inhibit desires for appetizing foods among a population that is strongly motivated to control their eating (i.e., chronic dieters)? Food is an ideal stimulus to use as it is natural reward that is both required and desired by animals and humans alike and for which chronic dieters are highly motivated to limit their consumption of (e.g., Heatherton, Polivy, & Herman, 1991). Given the work outlined above, we predicted that, compared to a group of non-depleted dieters, those who underwent self-regulatory depletion would show increased food cue-related activity in brain regions associated with the subjective reward value of food (i.e., orbitofrontal cortex, ventral striatum; Beaver et al., 2006; Demos et al., 2012, 2011; Gottfried, O'Doherty, & Dolan, 2003; Kringelbach, O'Doherty, Rolls, & Andrews, 2003; Wagner et al., 2012; for a meta-analysis see Van der Laan, De Ridder, Viergever, & Smeets, 2011). In addition, we predicted that depleted dieters would show impaired recruitment of lateral prefrontal regions (i.e., the inferior frontal gyrus) involved in cognitive control and self-regulation (Berkman, Falk, & Lieberman, 2011; Hare, Camerer, & Rangel, 2009; Kober et al., 2010; Somerville, Hare, & Casey, 2011).

Materials and Methods

Participants

Thirty-three healthy right-handed female chronic dieters were recruited from a larger pool of participants who completed the Restraint Scale (Heatherton, Herman, Polivy, King, & McGree, 1988), a validated measure of chronic dieting tendencies. Participants with restraint scale scores greater than 16 were considered to be chronic dieters (see Heatherton et al., 1991) and were invited to participate in the study. No mention of dieting was made during recruitment and participants remained unaware of our selection criteria until debriefing. Two participants were excluded from analysis due to excessive movement (i.e., several incidences of greater than 2mm movement) leaving a total of 31 participants (16 depleted, 15 control). Reaction time data for two participants were lost due to equipment malfunction. There were no differences between participants in the depletion and control group with respect to demographic and dieting characteristics (Table 1). Finally, all participants gave informed consent in accordance with the guidelines set by the Committee for the Protection of Human Subjects at Dartmouth College.

Attention Control Task

The attention control task was adapted from a commonly used task in studies of self-regulatory resource depletion (e.g. Schmeichel, Vohs, & Baumeister, 2003). During the task, participants viewed seven minutes of a documentary on Canadian bighorn mountain sheep (National Film Board of Canada, 1970). During the film, a series of one or two syllable distractor words (40 words total) appeared at the bottom of the screen and moved to the center over the course of 3 seconds. This task was preceded by a bogus eye tracking calibration session designed to convince participants that their gaze was being monitored during scanning. For more details on the task see Wagner & Heatherton (2012) and the supplementary methods in the supporting information available online.

Food Cue-Reactivity Task

The food cue-reactivity task was modified from our prior research on neural cue-reactivity to appetizing foods (Demos et al., 2011; Wagner et al., 2012). Categories and types of appetizing foods were selected based on pilot data in which 25 participants rated 250 high-quality food images according to how much they like and crave the food items. The final set of food images consisted of the top 30 most liked and craved images from each of three categories of tempting foods (meals, snacks and desserts). One hundred and eighty images involving people or natural scenes, such as landscapes, were chosen as a control condition (for representative stimuli, see Figure S1). The cue-reactivity task used a rapid event-related design with trials consisting of a single image (food, people or nature images) displayed for 2000ms with an inter-stimulus interval of 500ms. The order of trial types and the duration of the inter-trial interval (0ms, 2500ms or 5000ms) were pseudo-randomized. During the inter-trial interval, null event trials consisting of a white fixation cross against a black background were shown for 2500ms and were used to introduce jitter into the fMRI time series in order to increase the estimation efficiency of task effects. For each image, subjects indicated whether the image took place indoors or outdoors via button presses. This incidental task is serves to ensure that participants remain alert and naïve to the purpose of the study.

Procedure

Participants were instructed to refrain from eating or drinking for at least two hours prior to scanning so as to ensure that participants did not arrive satiated. Participants were informed that they would be participating in two unrelated experiments (understanding the gist of a movie and categorizing scenes). Instructions for the scene categorization task were given prior to the start of the experiment so as to minimize the delay between the self-regulatory depletion and food cue-reactivity task.

For the attention control task, participants in both conditions were instructed to keep their gaze on the video at all times. Participants in the control condition were told they could freely read the words, whereas participants in the depletion condition were instructed to inhibit reading while maintaining attention on the film. Participants in the depletion condition were not expected to successfully avoid reading all the distractor words, rather the purpose of the task is to have participants exert self-regulatory effort over an extended period of time.

After fMRI scanning, participants rated all the food images on how much they liked each item (on a scale from 1-9). Participants also completed a questionnaire probing for suspicion and rated the depletion task in terms of difficulty and cognitive fatigue (on a scale of 1 to 7). These ratings were combined to create a self-report index of the subjective experience of depletion.

Image Preprocessing and Analysis

Participants were scanned on a Philips Achieve 3.0 Tesla scanner (for additional image acquisition details see the supplementary methods in the supporting information available online). FMRI data were analyzed using the general linear model for event-related designs in SPM8 (Wellcome Department of Cognitive Neurology, London, UK) in conjunction with

a suite of tools for preprocessing and analysis (available at <http://github.com/ddwagner/SPM8w>). For each functional run, data were preprocessed to remove sources of noise and artifact. Images were corrected for differences in acquisition time between slices, realigned within and across runs, and unwarped to reduce residual movement-related image distortions. Data were normalized into a standard stereotaxic space (3mm isotropic voxels) based on the SPM8 EPI template that conforms to the ICBM 152 brain template space. Normalized images were spatially smoothed with a 6mm full-width-at-half-maximum Gaussian kernel.

For each participant, a general linear model (GLM) was constructed incorporating task effects and covariates of no interest (a session mean, a linear trend to account for low-frequency drift and 6 movement parameters) and convolved with a canonical hemodynamic response function (HRF). Additional nuisance regressors were included for two participants who exhibited a small number of isolated movements of more than 2mm (one regressor per affected volume and two additional regressors for the volume preceding and following the movement). In addition, we conducted a parametric modulation analysis in which participants' idiosyncratic "liking" ratings for each food image were used as a parametric modulator of the height of the hemodynamic response during food trials. Next, contrast images for each subject, comparing food vs. natural scenes were entered into a second-level, random-effects analysis. Monte Carlo simulations using AFNI's AlphaSim were used to calculate the minimum cluster size at an uncorrected threshold of $p < 0.001$ required for a whole brain correction of $p < 0.05$. Simulations (10,000 iterations) were performed using the mean across-subject smoothness estimated from the residuals obtained from each participant's 1st level GLM and resulting in a minimum cluster size of 33 contiguous voxels. Given our strong a priori predictions regarding the role of the ventral striatum in food cue-reactivity; a small volume correction was applied using an anatomical mask of the nucleus accumbens defined using the labels provided with the Harvard-Oxford probabilistic atlas of cortical and subcortical structures (Desikan et al., 2006). This resulted in a small volume correction of 9 contiguous voxels (cluster defining threshold of $p < 0.005$) for a correction of $p < 0.05$ within the volume of the nucleus accumbens. Subsequent between-group comparisons were conducted using ROI analyses. For each ROI, parameter estimates were extracted using spherical ROIs (6mm) centered on the peak voxel of clusters demonstrating an effect of food vs. natural scenes. For regions involved in representing the value of food items (i.e., orbitofrontal cortex, ventral striatum) ROI analyses are at $\alpha = 0.05$. For all other areas, subsequent between-group analyses were Bonferroni corrected for the total set of ROIs interrogated (i.e., $\alpha = 0.003$). As both groups contributed equally to the ROI-defining statistical map, ROIs are considered statistically unbiased with regards to between group effects.

In order to measure depletion related differences in functional connectivity, we conducted a psychophysiological interaction (PPI) analysis (Friston et al., 1997). In this analysis, the first eigenvariate of the time-series of voxels within seed ROIs (the OFC and striatum) was deconvolved from the HRF in order to generate an estimated neuronal time-series (Gitelman, Penny, Ashburner, & Friston, 2003) which was then multiplied by a vector coding for the onsets of food vs. other scenes and re-convolved with the HRF. This new

predictor was entered into a GLM along with a vector describing the onsets of each task condition, the original eigenvariate time-series for the seed region and covariates of no-interest (same as in preceding analysis). Parameter estimates for the PPI interaction term at the IFG were tested for context dependent (food vs. scenes) differential connectivity between depletion and control groups.

Results

Behavioral Results

There were no differences between the depletion and control groups on reaction times for performing indoor and outdoor judgments on food ($t(27) = 0.29, p = 0.78$; Depleted: $M = 1038\text{ms}$, Control: $M = 1019\text{ms}$) and natural scenes ($t(27) = 1.47, p = 0.15$; Depleted: $M = 995\text{ms}$; Control: $M = 921\text{ms}$). Participants in the depleted group scored higher on a subjective measure of cognitive depletion than participants in the control group ($t(29) = 2.81, p = 0.009$; Depleted: $M = 3.9$; Control: $M = 2.7$).

Brain Regions Demonstrating Food Cue-Related Activity and their Association with Ratings of Food Liking

Whole-brain random-effects analysis of the contrast of food vs. natural scenes across both groups revealed greater food-cue related activity in the left orbitofrontal cortex, right ventral striatum and the insula bilaterally (Figure 1, Table 2). ROI analysis revealed that participants' liking for each food item was a significant modulator of activity during food trials in the OFC ($t(30) = 2.07, p = 0.047$; mean β : 0.07) and marginally significant in the ventral striatum ($t(30) = 1.98, p = 0.056$; mean β : 0.05). Here the β represents the increase in signal change per unit of the parametric modulator (i.e., food liking).

Brain Regions Differentiating Between Depleted and Control Groups

Regions of interest analysis on regions derived from the contrast of food vs. natural scenes revealed that depleted participants demonstrated greater food cue-related activity in the OFC ($t(29) = 2.20, p = 0.036$, Figure 2a). The ventral striatum ROI demonstrated the same pattern of increased food-cue related activity in depleted compared to control participants, but the between group difference was not significant ($t(29) = 1.37, p = 0.18$, Figure S2). The effect of depletion on food cue-related activity was specific to regions involved in representing the rewarding and sensory aspects of food -- all other ROIs failed to show any difference between depleted and control participants¹.

Differential functional connectivity between OFC, ventral striatum and the IFG

Analysis of context (i.e., food vs. natural scenes) dependent functional connectivity between the OFC and the left IFG ROI defined from the above contrast (see Table 2 for coordinates) revealed reduced connectivity between these two regions in depleted as compared to control participants ($t(29) = 3.10, p = 0.004$, Figure 2b, for single subject representative plots see

¹We note that the left middle occipital gyrus ($p = 0.047$) and the insula bilaterally (left insula, $p = 0.042$; right insula: $p = 0.036$) did show an effect of group at an uncorrected α of 0.05 but failed to survive the correction for the total set of ROIs. No other ROI was significant at either corrected or uncorrected levels.

Figure S3 in the supporting information available online). A similar result was found when using the ventral striatum as a seed region ($t(29) = 2.04, p = 0.05$). Although we did not observe recruitment of the right IFG in the whole-brain analysis of task effects, given the strong theoretical prediction that the right IFG would be involved in inhibition and cognitive control (see discussion) we repeated the above analysis using a right IFG ROI generated by mirroring the center coordinates of the left IFG ROI along the x axis (i.e., MNI coordinates: $-45, 24, 18$ to $45, 24, 18$). Similar to the left IFG, this right IFG ROI showed differential functional connectivity as a function of depletion for the OFC ($t(29) = 3.16, p = 0.004$, Figure 2b) and ventral striatum ($t(29) = 2.73, p = 0.01$).

Correlation between OFC activity to food images and self-reported depletion

Analysis of food-cue related activity in the OFC with a self-report index of how depleted participants felt following the depletion task demonstrated a significant relationship in depleted ($r = 0.591, p = 0.016$) but not in the control group ($r = -0.04, p = 0.89$). Moreover, a moderated regression analysis (for more details see the supplementary results in the supporting information available online) revealed that participant group was a moderator of the relationship between depletion and OFC activity (Figure 3).

Discussion

The ability to inhibit responding to temptations fluctuates with prior exertion of self-control (Baumeister & Heatherton, 1996). Until recently, strength theories of self-regulation have generally assumed that self-regulatory depletion reduces the capacity for self-control but does not affect the intensity of impulses and desires. For example, Vohs and Heatherton (2000) demonstrated that dieters subsequently overeat following exertion on a prior self-control task. At the time, the authors interpreted this finding as resulting from weakened self-control rather than increased desire. Recent research, however, suggests that impulses and desires are themselves subject to modulation when people are in a depleted state (i.e., Schmeichel et al., 2010, Vohs et al., 2012). The current study demonstrates that prior exertion of self-regulatory effort alters the neural processing of a primary reward—in this case food—resulting in an exaggerated response to food items in the OFC. Consistent with the idea that there are individual differences in the capacity to engage in self-control (e.g., Baumeister & Heatherton, 1996; Hagger et al., 2010) we also show that activity in the OFC during food-cue exposure is correlated with the degree to which depleted individuals report being cognitively taxed by the depletion task. The OFC has been consistently implicated in food cue-reactivity studies (for a meta-analysis see Van der Laan et al., 2011) and has been shown to code for the subjective liking and pleasantness of foods as demonstrated in the current study with food cues as well as during actual food consumption (Kringelbach et al., 2003). Finally, with regards to the ventral striatum, a similar pattern was found although the magnitude of response in this region failed to differentiate between depleted and control participants (see Figure S2).

We also found that depleted participants exhibited reduced functional connectivity between the OFC and ventral striatum and the IFG bilaterally. Although the right IFG is more commonly implicated in inhibitory control (Aron, Robbins, & Poldrack, 2004), particularly

for inhibiting motor responses such as during go/nogo tasks (Somerville et al., 2011), the left IFG has also been implicated in response inhibition (e.g., Li, Huang, Constable, & Sinha, 2006) and in indexing the subjective evaluation of the cognitive costs of performing an action (McGuire & Botvinick, 2010). Moreover, the left IFG is involved in the regulation of emotion (McRae et al., 2010) as well as food and cigarette cravings (Kober et al., 2010) and, along with the right IFG, predicts a weakening of the relationship between craving and real-world smoking behavior (Berkman et al., 2011). Finally, the left IFG has also been found to predict healthy food decisions among dieters deciding between healthy and unhealthy foods (Hare et al., 2009). Considered together with the current findings, the available data offer partial support for a model in which it is the balance between prefrontal brain regions involved in executive control and brain areas involved in representing motivational salience and reward value that helps sustain self-regulation. However, it is important to note that this interpretation rests upon the observation of reduced functional connectivity between the IFG and OFC and the IFG and striatum during food trials. Contrary to what might have been expected, we found no evidence that depleted individuals under-recruited IFG compared to controls. Instead, depletion appears to disrupt the functional connectivity between these countervailing systems such that, for depleted individuals, these regions become uncoupled in the face of temptations.

In the present study we opted to keep dieters naïve to the nature of the study and to their special status as dieters by employing a simple categorization task. Thus, although chronic dieters were not explicitly instructed to regulate their responses to appetizing food items, they were nevertheless expected to engage in some degree of self-regulation as restricted eating is one of the central features defining this population (Vohs & Heatherton, 2000). We therefore suggest that our observation of differential connectivity between the OFC, striatum and IFG among depleted and non-depleted dieters likely reflects a failure among depleted dieters to restrain their responses to appetizing food cues, however further research, using explicit regulation paradigms (as in Kober et al., 2010), is needed to further examine this claim.

A limitation of this study is that we restricted our participant sample to include only chronic dieters. An open question is whether non-dieters would show increased food cue reactivity following depletion. We note that previous studies of nondieters have indicated robust reward-related brain activity to food cues in the absence of any experimental manipulations (e.g., Demos et al., 2011). Thus, although both chronic dieters and nondieters show evidence of food cue-related brain activity, we suggest that only dieters, by virtue of their tonic restraint, would show an exaggerated reward response to food cues following depletion.

The current findings complement recent behavioral work in which self-regulatory depletion has been found to intensify impulses and emotions (Vohs et al., 2012) as well as guide attention towards rewarding cues (Schmeichel et al., 2010). Moreover, these findings are also consistent with work showing that when dieters are in a “hot” affective state, they subsequently show stronger hedonic responses to food compared to non-dieters (Hofmann, Van Koningsbruggen, Stroebe, Ramanathan, & Aarts, 2010; Papies, Stroebe, & Aarts, 2007). Our findings also complement a recent study investigating the effects of self-regulatory depletion in the emotional domain (Wagner & Heatherton, 2012). In that study,

participants underwent the same attention-control task as used here, but were subsequently exposed to emotional scenes. Compared to non-depleted participants, depleted participants showed greater activity in the amygdala, a brain region implicated in emotional evaluations, when viewing negative scenes. Moreover, depleted participants also exhibited reduced functional connectivity with the ventromedial prefrontal cortex, a region often implicated in regulating emotional responses in the amygdala (e.g., Somerville et al. 2013). Thus, together with the present findings, these results offer converging neural evidence that temptations and emotional experiences are intensified when people are in a depleted state.

Since its inception, the strength model of self-regulation has had considerable influence on theories of self-control failure (Hagger et al., 2010). Nevertheless, recent accounts have raised questions about how depletion leads to self-regulation failure. In the current study we demonstrated that self-regulatory depletion increased neural responses to appetizing food cues in brain regions involved in representing the reward-value of food and simultaneously decreased the functional coupling between these areas and lateral prefrontal regions important for cognitive control. These results support a balance model of self-regulation (e.g., Heatherton & Wagner, 2011) and suggest that, in situations where people are highly motivated to restrain or otherwise moderate their behavior, impaired recruitment of the lateral prefrontal cortex may serve to release the brain's motivation and reward systems from inhibition. Such a release may result in increased reward sensitivity when people are confronted with temptations, which may then impel them to act on their desires, ultimately resulting in self-regulation failure.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

This research was supported by a grant from the National Institute on Drug Abuse (R01DA22582).

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Figure 1.

(A) Brain regions demonstrating greater activity to food versus natural scenes across both depleted and control groups. ($p < 0.05$, corrected). The yellow circle on the coronal and axial planes indicates the left orbitofrontal cortex. (B) Food-cue related activity in a region of the ventral striatum/nucleus accumbens ($p < 0.05$ corrected for the volume of the nucleus accumbens). The green outline serves to demarcate the borders of the anatomical volume of the nucleus accumbens that was used for small volume correction.

Figure 2.

(A) ROI analysis of the left orbitofrontal cortex (MNI Coordinates: $-30,33,-18$) demonstrated greater food-cue related activity in depleted as compared to control groups. The orbitofrontal cortex ROI was defined in an unbiased manner from the comparison of food vs. other scenes across both depletion and control groups. (B) Psychophysiological interactions analysis demonstrated reduced context-dependent (food vs. control scenes) functional connectivity between the IFG and OFC in depleted compared to control participants. Separate analysis of each group demonstrated a significant positive context-dependent coupling in the control group ($t(14)=2.77, p=0.015$) but no difference between food and control scenes in the depleted group ($t(15)=1.79, p=0.094$). Inset demonstrates the location of the orbitofrontal cortex (a) and inferior frontal gyrus (b) ROI. Error bars indicate SEM.

Figure 3.

Individual differences in self-reported depletion following the depletion task predicted subsequent food-cue related activity in the left orbitofrontal cortex in the depleted group ($r = 0.591$, $p = 0.016$) but not in the control group ($r = -0.04$, $p = 0.89$). A moderated regression analysis revealed that group was a marginally significant moderator of the relationship between self-reported depletion and OFC activity (β Group $\times$ Self-Reported Depletion = 0.331 , $p = 0.051$).

Table 1

Characteristics of dieters in the depletion and control conditions

	Depletion Group (<i>n</i> = 16)	Control Group (<i>n</i> = 15)
Age (years)	19.3	18.9
Weight (<i>lbs.</i>)	128.3	127.5
Estimated BMI (<i>kg/m²</i>)	20.7	20.6
Hours Slept	7.4	7.8
Hours Since Last Meal	7.4	5.7
Current Hunger (1 to 5)	2.6	2.7
Restraint Scale Score	19.2	18.1

Note: There were no between group differences in age, weight, estimated BMI, hours slept, hours since last meal, current hunger or restraint scale scores (all $p > 0.25$). Restraint was measured with the Revised Restraint Scale. Current hunger was rated on a scale of 1 to 5, with 1 being not at all hungry and 5 being extremely hungry.

Table 2

Brain regions demonstrating greater food cue-related activity across depletion and control groups

Brain Region	Side	BA	<i>t</i> -value	Coordinates of peak activation		
				<i>x</i>	<i>y</i>	<i>z</i>
Orbitofrontal cortex	L	11	4.48	−30	33	−18
Ventral Striatum	R	-	3.51	9	3	−6
Superior Temporal Gyrus	L	38	7.41	−39	3	−15
Insula [†]	L	13	5.96	−39	−6	3
Inferior Frontal Gyrus [†]	L	45	5.60	−45	24	18
Insula	R	13	6.53	45	−6	0
Posterior Cingulate Cortex	R	23	8.85	42	−21	24
Supplementary Motor Area	L	6	5.82	−9	15	63
Supplementary Motor Area [†]	L	6	4.97	−9	15	54
Dorsal ACC [†]	L	32	4.92	−6	24	36
Supplementary Motor Area	R	24	5.30	12	−9	54
Fusiform	R	37	6.48	51	−60	−18
Superior Parietal Lobule	L	7	5.58	−36	−66	54
Inferior Parietal Lobule [†]	L	19	5.37	−33	−69	42
Lingual Gyrus	L	18	8.37	−9	−94	−6
Middle Occipital Gyrus	L	37	5.38	−42	−66	−9
Cerebellum	L		11.31	−21	−51	−30
Thalamus	R		4.92	15	−21	3

Note: Regions showing greater activity to food vs. nature scenes across depleted and control groups are listed along with the best estimate of their location ($p < 0.05$, corrected). Coordinates are in Montreal Neurological Institute (MNI) stereotaxic space.

[†] Local maxima at least 8mm distant from the peak voxel. BA = approximate Brodmann's area; ACC = Anterior Cingulate Cortex.