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Monetary Reward Processing in Obese Individuals With and Without Binge Eating Disorder

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Abstract

Background—An important step in obesity research involves identifying neurobiological underpinnings of nonfood reward processing unique to specific subgroups of obese individuals.

Methods—Nineteen obese individuals seeking treatment for binge eating disorder (BED) were compared with 19 non-BED obese individuals (OB) and 19 lean control subjects (LC) while performing a monetary reward/loss task that parses anticipatory and outcome components during functional magnetic resonance imaging. Differences in regional activation were investigated in BED, OB, and LC groups during reward/loss prospect, anticipation, and notification.

Results—Relative to the LC group, the OB group demonstrated increased ventral striatal and ventromedial prefrontal cortex activity during anticipatory phases. In contrast, the BED group relative to the OB group demonstrated diminished bilateral ventral striatal activity during anticipatory reward/loss processing. No differences were observed between the BED and LC groups in the ventral striatum.

Conclusions—Heterogeneity exists among obese individuals with respect to the neural correlates of reward/loss processing. Neural differences in separable groups with obesity suggest that multiple, varying interventions might be important in optimizing prevention and treatment strategies for obesity.

Keywords

Binge eating disorder; fMRI; inferior frontal gyrus; insula; obesity; reward; ventral striatum

Neural reward systems—through their regulation of appetite, weight regulation, and treatment response—have been implicated in obesity (1–3). However, studies in obese populations have demonstrated both hyper- and hyporesponsivity reward neurocircuitry in response to food cues (4–8). These seemingly discordant findings might relate to heterogeneities among obese individuals (9). Obesity is associated with different forms of disordered eating behaviors. For example, groups with obesity and binge eating disorder (BED) differ from those with non-binge-related obesity on numerous behavioral and

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psychological dimensions (10). A current debate exists with regard to the applicability of "food addiction" to eating behaviors; although some investigators argue a lack of evidence (11), others propose that the construct seems particularly relevant to certain obese subgroups, such as BED (12,13).

Seemingly discordant findings might also reflect failures to adequately disambiguate phases relating to anticipatory and outcome processing (14). Reward anticipation is linked with ventral striatal (VS) activity, whereas greater medial prefrontal cortex activity is associated with reward notification or the outcome phase of reward processing (15–18). Food-cue studies making anticipatory-consummatory distinctions report greater anticipatory responsiveness in the VS, midbrain, amygdala, and thalamus relative to consummatory phases of reward processing in healthy individuals (19,20). Palatable food consumption is associated with greater activity in the orbitofrontal cortex (OFC) and insula, with increased responsiveness observed in obese individuals (19,21,22). In obesity, the anticipatory-consummatory distinction is particularly important, because energy intake seems strongly influenced by anticipatory signaling rather than actual food consumption (23). Heightened anticipation of food reward is posited as a trigger for overeating in obese individuals (20,24).

To date, neuroimaging studies distinguishing anticipatory/ consummatory processing in populations with disordered eating provide complex findings. Obese, relative to lean, individuals show increased activity in the insula and inferior frontal gyrus (IFG) during food anticipation (22). However, in bulimia nervosa, a disorder characterized by binge eating, food anticipation is associated with diminished prefrontal and insula activity, relative to nonbinge-eating individuals (25). Striatal activity is associated with reward processing tasks (15–18,26,27), and altered striatal responses are associated with obesity and weight gain; however, although some studies demonstrate diminished activity after palatable food intake in obese individuals, others report increased striatal responding (6,22,28,29).

Similarly, the addiction literature includes seemingly ambiguous findings in reward processing, even when distinguishing anticipatory/consummatory components. For example, increased striatal activity has been reported in cocaine dependence during anticipatory processing (30), whereas diminished anticipatory VS responses have been noted in alcohol dependence (31) and pathological gambling (32). These differences might relate to specific disorders, methodological/analytical considerations, treatment-seeking status, or anatomical delineations of the VS; additional differences might relate to types of reinforcers (e.g., addiction-related/unrelated).

Although many neuroimaging studies examine reward processes related to food cue paradigms in obese populations, there is a dearth of investigations into non-food reward processing in obesity (33,34). Understanding generalized reward processing in obesity is important, because alterations in reward circuitry might represent vulnerabilities for disordered eating. The current study used functional magnetic resonance imaging (fMRI) to examine monetary reward processing during the anticipation and receipt of wins/losses in obese individuals with and without BED and a lean comparison (LC) group. Binge eating disorder differs significantly from other forms of obesity and eating disorders in numerous behavioral, body-image, psychological, and psychiatric markers (10,35,36). However, to date, only two neuroimaging studies have examined the bio-behavioral correlates of this disorder relative to other obese conditions. The first observed differences in overweight BED participants relative to overweight and lean groups without BED in responses of the ventromedial prefrontal cortex (vmPFC) to food cues (37). Recently, we observed brain activation differences between obese individuals with and without BED during a cognitive control task, with the BED group demonstrating relatively diminished activation in the IFG, vmPFC, and insula (38).

To investigate further differences in obese individuals with and without BED, we employed a widely used monetary incentive delay task (MIDT) to examine reward/loss processing (16,17,32,39,40). We hypothesized that the BED group would show diminished responding in the VS during anticipatory phases, whereas the OB group would demonstrate increased VS activity relative to the LC group. We hypothesized that, consistent with fMRI studies in bulimia (25), during the outcome phase the BED group would demonstrate decreased vmPFC, insula, thalamus, and IFG activity relative to the non-BED groups. Similarities in BED and OB groups were examined, given potential similarities between obese individuals in the neural correlates of reward processing.

Methods and Materials

Participants

Participants included 57 adults 19–64 years of age (mean age: 38.9, 34 female), where 64.9% (n = 37) identified as Caucasian, 29.0% (n = 17) identified as African American, 5.3% (n = 3) identified as Native American, and 1.8% (n = 1) identified as Asian American; 5.3% (n = 3) identified themselves as Hispanic, and 94.7% (n = 54) identified as non-Hispanic. Demographic information is in Table 1 and Supplement 1. Age was included as covariates in all group contrast analyses, given group differences in age and to control for potential age-related effects. Body mass index (BMI) in the BED group ranged from 30.1 to 44.1. The OB group included 19 individuals with a BMI ranging from 30.4 to 41.6 and the LC group consisted of 19 individuals with BMIs ranging from 20.4 to 24.6. The BED and OB groups did not differ on mean BMI, and as expected, these groups had higher BMIs than the LC group.

The obese BED group consisted of 19 treatment-seeking participants enrolled in a randomized placebo-controlled trial testing 4-month treatments of sibutramine and cognitivebehavioral-self-help interventions, alone or in combination. Following baseline measures described here, participants underwent the fMRI protocol before starting the treatments, which were delivered for 4 months. The proposed DSM-5 criteria for BED (www.dsm5.org) was used to verify that all individuals in the BED group met criteria, but no individuals in the OB or LC groups had a history or current expression of binge eating or other disordered eating behaviors.

Measures

MIDT—All participants completed the MIDT; the task and experimental methods are described elsewhere (32,39) and in the Methods section of Supplement 1.

fMRI Acquisition and Analysis—Images were obtained with Siemens TIM Trio 3T MRI systems (Siemens, Malvern, Pennsylvania). Image acquisition and analysis methods are detailed in Supplement 1. Functional images were preprocessed with SPM5 (Welcome Functional Imaging Laboratory, London, UK), normalized to the Montreal-Neurological-Institute template and smoothed with a 6-mm kernel full-width-at-half-maximum. First-level modeling was conducted with robust regression (41) to reduce the influence of outliers (42). Motion and high-pass filter parameters were included as additional regressors of no interest. The Neuroelf analysis package (www.neuroelf.net) was used for second-level random effects analysis. Correction for multiple comparisons was conducted with Monte-Carlo simulation (e.g., AlphaSim), with combined voxel-wise and cluster thresholds to result in a family-wise-error rate of 5%. To examine task-related brain activations, we contrasted: 1) anticipation of monetary gain versus anticipation of no monetary outcome for the prospect (A1) and anticipation of notification (A2) phases (A1Win and A2Win, respectively); 2) anticipation of monetary loss versus anticipation of no monetary outcome for the A1 and A2 phases (A1Loss and A2Loss, respectively); 3) “Win” versus “Neutral” outcome trials (OCWin); and 4) “Loss” versus “Neutral” outcome trials (OCLoss). See Supplement 1 for more information and Balodis *et al.* (32) depicting trial structure. To examine between-group differences, we compared activity in BED, OB, and LC groups during A1Win, A2Win, OCWin, A1Loss, A2Loss, and OCLoss in pair-wise *t* tests. In addition to whole-brain contrasts, 2 region-of-interest analyses were performed. These analyses focused on the VS, with coordinates from a meta-analysis of brain circuits recruited during anticipation of monetary incentives (Figure 2) (43) and coordinates encompassing the nucleus accumbens (Figure 3) (26).

Results

The A1 contrast and behavioral and affective response results are located in Supplement 1, given space limitations and the relevance of the A2 and OC phases to addictive processes. Additionally, a conjunction analysis listing overlapping activations across obese groups (BED + OB groups combined) is listed in Table S2 in Supplement 1. All group differences are listed in Table 1. In the following, results highlight and describe group differences related to our hypotheses (i.e., fronto-striatal areas). Results of region-of-interest analyses are depicted in Figures 2 and 3.

OB Versus LC

See Figure 1A and Table 2.

A2Win—During A2Win, OB-LC contrasts demonstrated increased activity in the right IFG extending medially to the OFC and in the bilateral thalamus extending to the right caudate, VS (Figure 2C, Figure 3C), and hypothalamus.

A2Loss—During A2Loss, OB–LC contrasts demonstrated increased activity in left IFG extending bilaterally to the right IFG, OFC, and vmPFC; right medial frontal gyrus extending laterally to middle frontal gyrus and IFG; and left midbrain substantia nigra extending medially to red nucleus and lentiform nucleus.

OCWin—During OCWin, OB–LC contrasts demonstrated relatively decreased activity in the left precentral gyrus extending dorsally to the middle frontal and postcentral gyrus.

OCLoss—During OCLoss, OB–LC contrasts demonstrated diminished activity in the left precentral gyrus extending to the medial frontal and postcentral gyrus.

BED Versus LC

See Figure 1B and Table 2.

A2Win—During A2Win, BED–LC contrasts demonstrated relatively increased activity in dorsal caudate extending to middle frontal gyrus, insula, and claustrum and in left cingulate gyrus extending to caudate (Figure 2D). Decreased activity was observed in the dorsal medial frontal gyrus.

A2Loss—During A2Loss, BED–LC contrasts demonstrated relatively increased activity in right caudate extending to IFG. Relatively reduced activity was observed in right middle frontal gyrus extending dorsally to the medial frontal gyrus.

OCWin—During OCWin, BED–LC contrasts demonstrated relatively diminished activity in right superior temporal gyrus extending to insula, cingulate gyrus, and posterior cingulate; left inferior parietal lobule extending to insula, posterior cingulate, superior/middle temporal gyrus, VS, caudate, postcentral gyrus, precuneus, cuneus, superior/middle occipital gyrus, and culmen; bilateral anterior cingulate extending laterally to right IFG, caudate, and claustrum; bilateral medial frontal gyrus; and right VS.

OCLoss—During OCLoss, BED–LC contrasts demonstrated relatively decreased activity in left precentral gyrus extending to right cingulate gyrus, bilateral anterior cingulate, left paracentral lobule, right postcentral gyrus, and right paracentral lobule; right superior temporal gyrus extending to transverse temporal gyrus, postcentral gyrus, and insula; left insula extending to precentral gyrus and postcentral gyrus; left posterior cingulate extending to lingual gyrus, bilateral precuneus, and cuneus; and right midbrain extending to thalamus and culmen.

BED Versus OB

See Figure 1C and Table 2.

A2Win—During A2Win, BED–OB contrasts showed relatively diminished activity in the lentiform nucleus extending bilaterally to the VS (Figure 2B, Figure 3B), hypothalamus, thalamus, caudate, putamen, and midbrain red nucleus; in the right cingulate gyrus extending bilaterally to the medial/superior frontal gyrus; right insula extending to the superior temporal gyrus; and in the left precentral gyrus extending to the IFG.

A2Loss—During A2Loss, BED–OB contrasts demonstrated relatively diminished activity in midbrain red nucleus extending to thalamus, bilateral VS, and substantia nigra; medial frontal gyrus extending to postcentral gyrus, cingulate gyrus, inferior parietal lobule, postcentral gyrus, and superior frontal gyrus; left insula extending to superior temporal gyrus; middle frontal gyrus extending to anterior cingulate and medial frontal gyrus; and left precentral gyrus extending to the postcentral gyrus.

OCWin—During OCWin, BED–OB contrasts demonstrated relatively diminished activity in insula, lentiform nucleus, para-hippocampal gyrus, cuneus, thalamus, and superior temporal gyrus; right superior temporal gyrus extending to insula, precentral gyrus, and IFG; right medial frontal gyrus extending to anterior cingulate, bilateral VS, and caudate; and left caudate.

OCLoss—During OCLoss, BED–OB contrasts demonstrated no group differences in fronto-striatal regions (Table 1 lists all group differences).

Discussion

Significant differences were observed between BED, OB, and LC groups in ways that partially confirmed our hypotheses: significant anticipatory differences in the VS were observed during the A2 win/loss phases in BED–OB (but not BED–LC) contrasts; BED–OB comparisons during these phases revealed diminished anticipatory VS responses in BED, whereas OB–LC contrasts showed heightened VS responses in OB. These patterns also held for group differences in the midbrain, thalamus, and amygdala, suggesting differential recruitment of affective and/or motivational circuitry (44,45). Outcome processing in BED participants was associated with diminished prefrontal and insula activity relative to both non-BED groups. The biological and clinical implications are discussed here with respect to differences between group contrasts during anticipatory and outcome reward phases.

Anticipation Processing

Consistent with our hypotheses, anticipatory processing was associated with diminished bilateral VS activity in BED relative to OB participants. Conversely, OB–LC contrasts revealed increased bilateral VS recruitment during this phase in OB participants. Additionally, divergent BED–OB signaling was evidenced in midbrain, amygdala, and thalamus—areas previously identified in food cue paradigms as more responsive during anticipatory relative to consummatory reward processes (19,20). These results, therefore, provide some clarification of seemingly ambiguous hypo- versus hyperactivity reward-processing findings in obesity and underline the importance of differentiating between obesity subtypes and anticipatory-outcome reward phases. The VS, particularly the nucleus accumbens, has been strongly implicated in reward processing, especially as it relates to changes in affective state and goal-directed behaviors (46–48). Our findings of diminished striatal response in the BED group, relative to the OB group, across the A2 win/loss phases accords with MIDT findings in other populations characterized by problems with impulse control, including those with pathological gambling, attention-deficit/hyperactivity disorder, alcohol dependence, and positive family histories for alcoholism (31,32,39,49,50). Similar to pathological gambling–related findings (37), relative frontostriatal hypoactivity in BED participants was less phase-specific than hypothesized. The relatively diminished fronto-striatal activity occurred in both anticipatory and outcome phases and win and loss conditions (Figure 1), indicating in BED a generalized pattern of diminished fronto-striatal processing of rewards and losses. Additionally, BED–LC and BED–OB contrasts produced a similar pattern of differences across the outcome phases on the MIDT, particularly in insular and striatal regions. However, few differences in fronto-striatal regions during the anticipation phase in BED–LC contrasts suggest that the BED group might best be characterized by alterations during outcome phases, whereas the OB group is distinguished through hyperactivity during anticipatory phases.

Relevance to Addiction Theories

Diminished anticipatory processing might represent an important precursor in the development of BED. “Reward deficiency syndrome” posits that individuals with low baseline reward neurocircuitry activity might consume food or engage in addictive behaviors in compensatory efforts to stimulate activity in these areas (51). Altered midbrain responses encompassing the substantia nigra in both the A2W and A2L phases in the BED-OB and the OB–LC contrasts suggest alterations in dopaminergic neural pathways. Indeed, the VS, hypothalamus, thalamus, and prefrontal cortex represent predominant projection areas of the mesocorticolimbic dopamine system, consistent with the role of this neurotransmitter in reward processing (52,53). Although fMRI cannot definitely relate activity changes to dopamine, conjoint fMRI and positron emission tomography studies demonstrate increased dopaminergic activity in prefrontal cortical areas as individuals anticipate and receive monetary rewards (54). Dopaminergic alterations are noted in BED (55–57), and striatal dopamine release during food stimulation is positively associated with dietary restraint (58). Nonetheless, a BED-hypo-active/OB-hyperactive dopaminergic model might oversimplify underlying processes; alterations might relate to specific disorder stages, such that initial hypersensitivity of this system might become downregulated with intermittent overeating of high-fat or sugary foods (59–61). Consistent with the incentive-salience theory, the hedonic impact (i.e., “liking”) of consummatory processing might decrease after over-consumption, whereas the incentive-salience (i.e., “wanting”) component is heightened. In the current study, BED participants demonstrated diminished anticipatory processing relative to the OB group to monetary cues; it is possible that exposure to food cues (i.e., disorderspecific stimuli) might increase activity in fronto-striatal networks (37).

In contrast to the BED group, OB–LC group differences were mostly contained within the anticipatory phases. Findings in the OB (relative to LC) group of increased medial/lateral OFC, striatum, amygdala, and hippocampal activation during anticipatory processing are consistent with similar response patterns noted during presentation of food cues (7) and support the idea of greater reward anticipation in this group.

Outcome Processing

Consistent with our hypotheses, BED participants demonstrated relatively diminished activity in prefrontal and insular regions during outcome phases, relative to both OB and LC groups. These findings are consistent with reports in full and subthreshold bulimia, where individuals demonstrate diminished activity in left middle frontal gyrus, insula, and right precentral gyrus during palatable food consumption (25). Additionally, vmPFC and right insula atrophy are linked to compulsive binge-eating etiology (62). In both BED–OB and BED–LC contrasts, diminished bilateral insula activity extending to the IFG is evident in BED participants. The insula constitutes the primary taste cortex but is also implicated in homeostatic signaling (63–65). Therefore, the results support the idea of altered generalized reward processing in BED. Altered interoceptive awareness through blunted insula activity, particularly during outcome processing, suggests an impaired ability to integrate reward information relating to the current state of the individual. Additionally, the IFG is implicated in the interaction between cognitive and motivational processing during inhibitory control (66–68); therefore collective diminished IFG and insula signaling might have implications for gauging hunger/satiety signals.

Strengths, Limitations, and Future Directions

To our knowledge, the current study is the first fMRI investigation into generalized reward processing across distinctive reward phases and between obesity subgroups, including those with BED. The application of a reward-processing paradigm in obese groups displaying different eating behaviors provides greater insight into potential biomarkers of each phenotype. In this way, the current study parses specific neural correlates related to eating-behavior patterns from those associated with obesity. Additionally, the fMRI task provides the opportunity to examine neurofunctional patterns associated with reward/loss processes that might promote specific eating patterns.

The current study is limited by several factors. The low number of male participants in the BED group precluded an examination of gender differences; administration of eating questionnaires across all groups might also have identified other important eating characteristics. Previous studies have reported differences related to BED severity in clinical versus community samples (69); therefore, it is possible that the treatment-seeking nature distinguished the BED from the OB and LC groups. Some of the whole-brain findings do not survive a conservative Bonferroni correction for multiple comparisons relating to the six phases of the MIDT and the three diagnostic groups examined.

Future research could further examine commonalities between BED and OB groups; in the current study conjunction analyses identified overlap in more dorsal and posterior areas (Table S2 in Supplement 1). Additionally, little overlap was observed between obese groups in the BED–LC and OB–LC contrasts. Concordant areas appeared mostly during outcome phases and in more dorsal posterior regions, including diminished posterior cingulate, precuneus, and precentral gyrus activity during both outcome phases. These areas are implicated in reward expectation and the control of attention; for example, the posterior cingulate is ascribed a role in signaling environmental change, including reward outcome, with increased activity corresponding with changes in internal state or environmental

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variables (70). Diminished activity in these areas in the obese groups suggests alterations in attention and motivation during feedback in the outcome phases.

Future studies should also examine possible differences related to gender, smoking status, and treatment-seeking behaviors in obese individuals. Another important step will involve understanding how these neural systems interact with homeostatic mechanisms (71,72) and additionally relate these to the chronicity/duration of obesity and/or BED. Longitudinal studies could further provide temporal links between weight changes and reward system processing and identify biological markers related to food intake preceding obesity development. Although the current experimental design cannot discriminate whether these differences are a cause or consequence of obesity or binge eating, they nonetheless have significant implications for the treatment of obesity. Therapies focused on stimulating corticostriatal limbic activity might represent important treatment strategies for BED. More broadly, these findings suggest the potential relevance of health policies in regulating high-fat, high-sugar foods that might alter reward responsivity in those at risk for binge eating and obesity (73).

Conclusions

The current study represents an important step in examining groups of people with obesity and brain correlates of non-food reward processing. Findings of reduced cortico-striatal processing in BED participants across anticipatory and outcome reward phases relative to OB and LC groups suggest reduced recruitment of networks involved in reward processing and selfregulation. These data also provide evidence of similar neurocircuitry alterations mediating reward processing in other disorders of impulse control, such as pathological gambling and alcohol dependence. The inclusion of both BED and OB groups represents a key step in considering how complex behaviors contribute to obesity. Altogether, the current findings suggest divergent neural substrates in abstract reward processing distinguishing specific subgroups of obese individuals. These data might provide insight into seemingly ambiguous findings of VS activity in obesity research.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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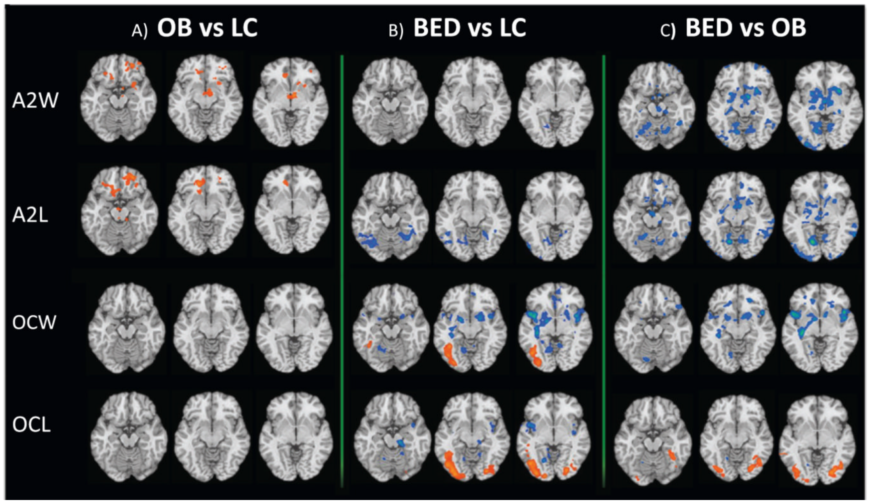

Figure 1.
Group differences on the Monetary Incentive Delay Task in ventral fronto-striatal areas in obese individuals with binge eating disorder (BED) (n = 19), obese individuals without BED (OB) (n = 19), and a lean comparison (LC) (n = 19) group at z = −17, −11, −6. Brain activation maps demonstrate differences in the A2 winning phase (A2W) (associated with the anticipation of potentially winning money), the A2 losing phase (A2L) (associated with the anticipation of potentially losing money), the outcome winning phase (OCW) (associated with the receipt of a monetary reward), and the outcome losing phase (OCL) (associated with the loss of money). All contrast maps are thresholded at an uncorrected level of $p < .05$ two-tailed and family-wiseerror-corrected at $p < .05$. Blue color demonstrates areas where subjects show relatively less activation, and red color indicates where participants show relatively greater activation. The right side of the brain is on the right.

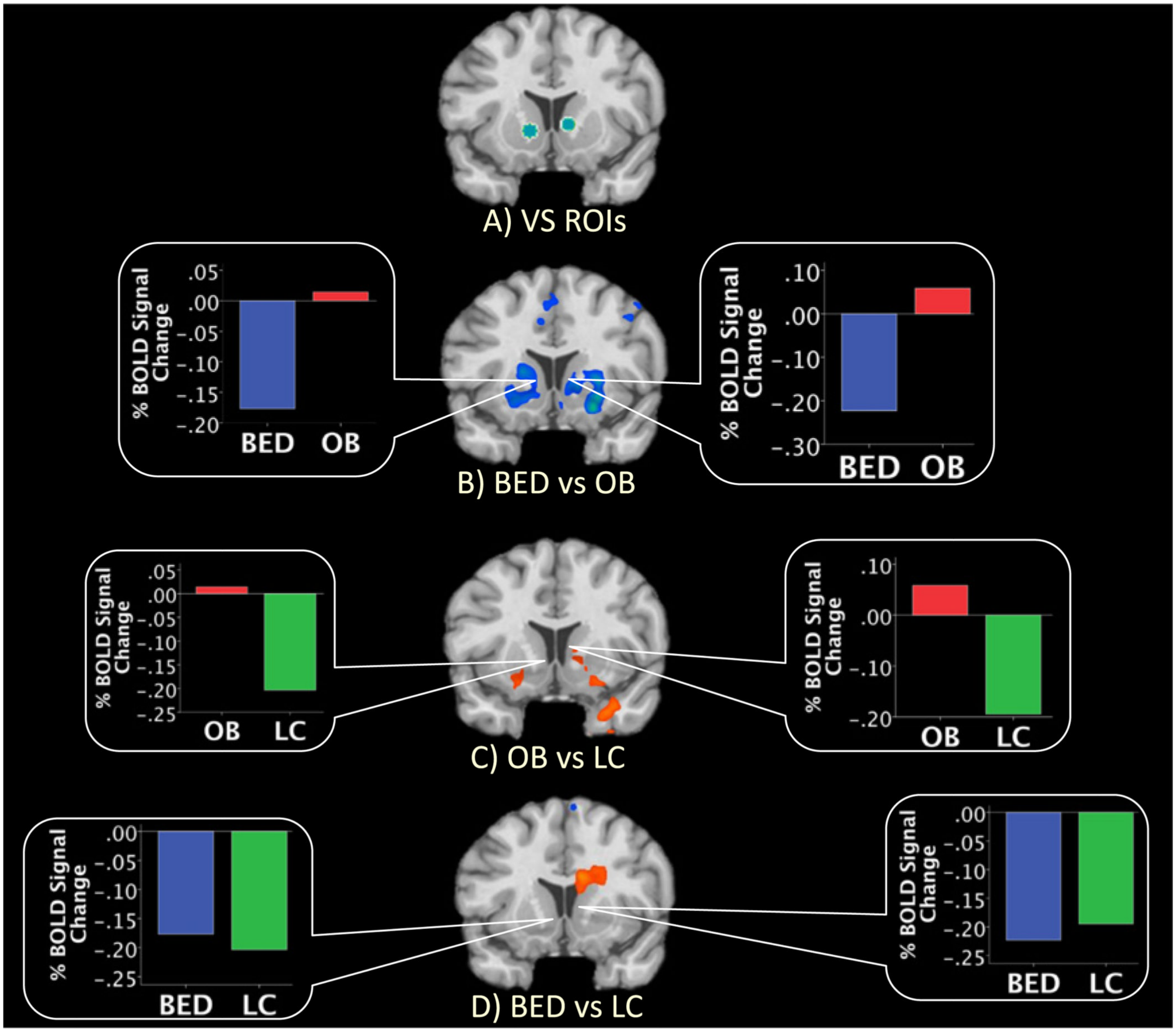

Figure 2.

Coronal view of ventral striatal regions of interest (ROIs) with coordinates reported by Knutson and Greer (43). (**A**) Blue spots indicate a 5-mm sphere around the ventral striatum on the left [−12, 10,−2] and right [10, 8, 2] sides. (**B**) Coronal slice y = 10 demonstrates whole brain contrast between BED and OB groups during the A2 winning phase. Graphs depict percentage blood oxygen level–dependent (BOLD) signal change extracted from each 5-mm ROI on the right and left sides for the BED (blue) and OB (red) groups. **(C)** Coronal slice y = 10 demonstrates whole brain contrast between OB and LC groups during the A2 winning phase. Graphs depict percentage BOLD signal change extracted from each 5-mm ROI on the right and left sides for the OB (red) and LC (green) groups. **(D)** Coronal slice y = 10 demonstrates whole brain contrast between BED and LC groups during the A2 winning phase. Graphs depict percentage BOLD signal change extracted from each 5 mm ROI on the right and left sides for the BED (blue) and LC (green) groups. The right side of the brain is on the right. Abbreviations as in Figures 1 and 2.

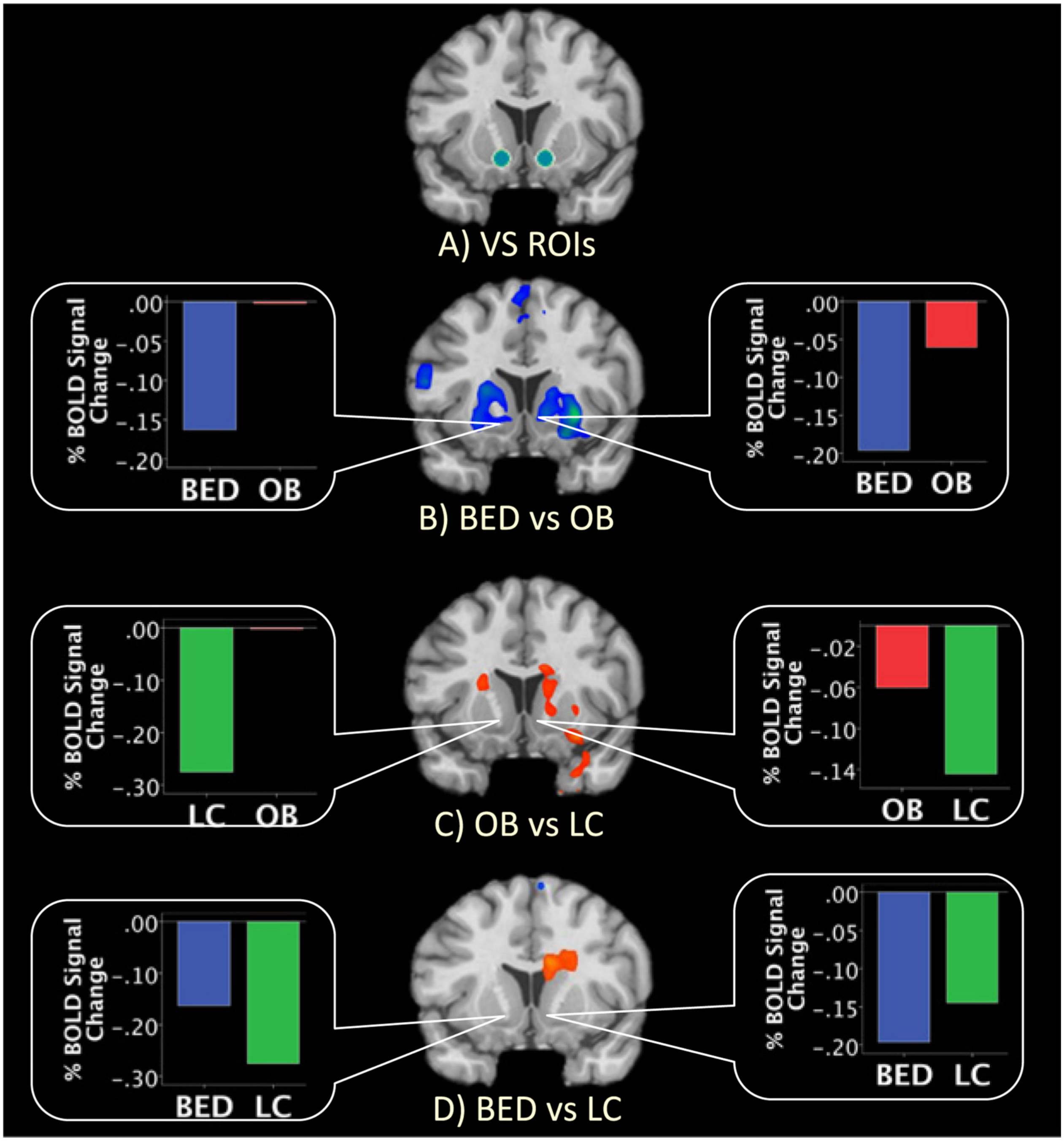

Figure 3.
Coronal view of ventral striatal ROIs with coordinates based on reward processing findings by Breiter *et al*. (15). (**A**) Blue spots indicate a 6-mm sphere around the ventral striatum on the left (−12, 7, −10) and right (12, 7, −10) sides. (**B**) Coronal slice y = 10 demonstrates whole brain contrast between BED and OB groups during the A2 winning phase. Graphs depict percentage BOLD signal change extracted from each 6-mm ROI on the right and left sides for the BED (blue) and OB (red) groups. (**C**) Coronal slice y = 10 demonstrates whole brain contrast between OB and LC groups during the A2 winning phase. Graphs depict percentage BOLD signal change extracted from each 6-mm ROI on the right and left sides

for the OB (red) and LC (green) groups. (**D**) Coronal slice y = 10 demonstrates whole brain contrast between BED and LC groups during the A2 winning phase. Graphs depict percentage BOLD signal change extracted from each 6-mm ROI on the right and left sides for the BED (blue) and LC (green) groups. The right side of the brain is on the right. Abbreviations as in Figures 1 and 2.

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Table 1

Participant Demographic and BMI Data

	BED	OB	LC	Test Statistic
n	19	19	19	—
Male/Female	5/14	9/10	9/10	$\chi^2_{2,57} = 2.3$, $p > .05$
Age (SD)	43.7 (12.7)[a]	38.3 (7.5)	34.8 (10.7)	$F_{2,54} = 3.5$, $p < .05$
Race: White/Black/Native American/Asian	14/3/2/0	11/7/1/0	12/6/1/1[b]	$\chi^2_{6,57} = 6.0$, $p > .05$
Ethnicity: Non-Hispanic/Hispanic	18/1	18/1	18/1	$\chi^2_{2,57} = .0$, $p > .05$
BMI (SD)	36.7 (4.05)	34.6 (3.5)	23.3 (1.1)[a]	$F_{2,54} = 100.1$, $p < .05$

BMI, body mass index; BED, binge eating disorder; LC, lean control subjects; OB, non-BED obese individuals.

[a] $p < .05$.

[b] One individual identified as both Black and Native American, therefore $n > 19$.

Table 2

Group Differences During MIDT

MIDT Phase	Structure	BA	Left/ Right	MNI Coordinates x	y	z	k	*T* Value
OB vs. LC								
A1Win	Insula/Inferior Parietal Lobule/Superior Temporal Gyrus	13	L	−54	−36	−24	152	−3.88
	Precentral Gyrus	4	R	45	−6	60	424	−3.77
	Cerebellum/Uvula	—	L	−3	−69	−39	121	−3.67
	Precentral Gyrus/Insula/Postcentral Gyrus/Superior Temporal Gyrus	6	L	−39	−15	33	497	−3.53
	Lingual Gyrus/Culmen/Declive	18	R	9	−72	−3	228	−3.38
	Middle Temporal Gyrus	19	L	−51	−81	21	133	−3.29
	Cingulate Gyrus[a]	24	L	−3	−9	51	110	−3.02
A1Loss	Middle Frontal Gyrus/OFC	11	R	27	42	−21	108	−3.87
	Parahippocampal Gyrus/Fusiform Gyrus	20	L	−39	−18	−27	105	−4.09
	Postcentral Gyrus/Insula	13	R	54	−12	21	111	−4.05
	Culmen/Declive/Fusiform Gyrus	—	L	−18	−51	−27	237	−3.83
	Inferior Parietal Lobule/Superior Temporal Gyrus/Insula	40	L	−57	−42	21	118	−3.64
	Declive/Culmen/Lingual Gyrus	—	L	0	−72	−18	305	−3.44
	Medial Frontal Gyrus/Paracentral Lobule/Cingulate Gyrus	6	L	−6	0	54	131	−3.36
	Precentral Gyrus/Postcentral Gyrus	4	L	−39	−15	36	197	−3.33
A2Win	Inferior Frontal Gyrus/OFC	11	R	21	33	−24	113	3.79
	Inferior Frontal Gyrus/Middle Frontal Gyrus/Claustrum	46	L	−42	30	12	105	3.74
	Cingulate Gyrus/Caudate	31	L	−18	−21	42	133	3.59
	Thalamus/Cingulate Gyrus/Hypothalamus/Caudate/Lentiform Nucleus/Ventral Striatum	—	R	9	−3	−3	195	3.54
	Cingulate Gyrus/Superior Parietal Lobule[a]	31	L	−24	−42	21	114	3.07
A2Loss	Inferior Frontal Gyrus/vmPFC/OFC/Ventral Striatum	11	L	−24	33	−27	181	4.33
	Middle Frontal Gyrus/OFC	11	R	24	45	−15	131	3.66
	Medial Frontal Gyrus/Middle Frontal Gyrus/Inferior Frontal Gyrus/Anterior Cingulate[a]	9	R	15	36	21	124	3.06
	Culmen/Midbrain Substantia Nigra/Red Nucleus[a]	—	R	12	−33	−24	91	2.92
OCWin	Middle Temporal Gyrus/Superior Occipital Gyrus/Cuneus	19	L	−48	−84	24	95	−3.51

MIDT Phase	Structure	BA	Left/ Right	MNI Coordinates x	y	z	k	*T* Value
	Precentral Gyrus/Middle Frontal Gyrus/Postcentral Gyrus	4	L	−33	−15	51	148	−3.27
	Precuneus/Posterior Cingulate	23	L	0	−57	21	101	−3.21
OCLoss	Precuneus/Posterior Cingulate	23	L	0	−60	21	196	−4.15
	Middle Temporal Gyrus/Precuneus	19	L	−51	−81	21	158	−3.96
	Middle Temporal Gyrus/Superior Occipital Gyrus/Precuneus	39	R	−27	−9	60	217	−3.64
	Precentral Gyrus/Medial Frontal Gyrus/Postcentral Gyrus	6	L	−27	−9	60	351	−3.58
BED vs. LC								
A1Win	—	—	—	—	—	—	—	—
A1 Loss	Inferior Frontal Gyrus[a]	45	R	45	30	9	106	3.03
	Middle Occipital Gyrus	18	L	−30	−99	12	115	−3.30
A2Win	Caudate/Middle Frontal Gyrus/Claustrum/Inferior Frontal Gyrus	46	R	9	6	24	226	3.99
	Cingulate Gyrus/Caudate	24	L	−18	−18	39	257	3.87
	Caudate/Superior Temporal Gyrus	—	R	33	−45	9	287	3.56
	Cuneus/Lingual Gyrus	19	L	−9	−93	33	174	−4.27
	Medial Frontal Gyrus	6	R	3	0	63	108	−4.21
A2Loss	Caudate/Inferior Frontal Gyrus	—	R	24	24	21	161	3.71
	Superior Occipital Gyrus/Cuneus	19	R	39	−87	30	133	−3.99
	Cuneus/Middle Occipital Gyrus/Middle Temporal Gyrus/Lingual Gyrus	18	L	−12	−72	12	520	−3.73
	Fusiform Gyrus/Posterior Cingulate/Culmen	37	R	36	−54	−15	217	−3.47
OCWin	Middle Temporal Gyrus/Inferior Occipital Gyrus	37	L	−39	−57	−9	255	3.39
	Superior Temporal Gyrus/Precuneus/Insula/Precentral Gyrus/Cingulate Gyrus/Posterior CingulateLingual Gyrus/Supramarginal Gyrus	22	R	63	−30	24	1648	−5.35
	Inferior Parietal Lobule/Insula/Posterior Cingulate/Superior Temporal Gyrus/Cuneus/Precentral	40	L	−69	−33	30	3606	−4.95
	Gyrus/Ventral Striatum/Caudate/Precuneus/Postcentral Gyrus/Cingulate Gyrus Anterior Cingulate/Inferior Frontal Gyrus/Caudate	24	L	0	21	24	271	−3.93
	Medial Frontal Gyrus	10	L	−6	54	12	144	−3.52
	Ventral Striatum/Lentiform Nucleus		R	21	3	−12	105	−3.41
OCLoss	Inferior Occipital Gyrus/Middle Occipital Gyrus/Lingual Gyrus/Middle Temporal Gyrus	18	L	−33	−90	−9	406	3.93
	Middle Occipital Gyrus	18	R	27	−84	−12	113	3.56
	Precentral Gyrus/Cingulate Gyrus/Anterior Cingulate/Paracentral Lobule	4	L	−21	−21	54	581	−4.54

MIDT Phase	Structure	BA	Left/ Right	MNI Coordinates x	y	z	k	*T* Value
	Superior Temporal Gyrus/Transverse Temporal Gyrus/Postcentral Gyrus/Insula	13	R	54	−36	21	624	−4.46
	Insula/Precentral Gyrus/Inferior Parietal Lobule/Postcentral Gyrus	13	L	−42	−6	0	547	−4.42
	Posterior Cingulate/Precuneus/Lingual Gyrus/Cuneus	30	L	−24	−57	9	791	−4.35
	Angular Gyrus	39	L	−48	−75	36	178	−3.77
	Thalamus/Midbrain/Culmen	—	R	15	−27	−15	107	−3.66
BED vs. OB								
A1Win	Inferior Frontal Gyrus/Insula	13	L	−42	12	15	121	4.10
	Middle Frontal Gyrus/Caudate/Putamen/Claustrum	46	R	39	21	15	162	3.60
	Precentral Gyrus/Postcentral Gyrus	31	R	39	−12	45	99	3.36
	Lingual Gyrus/Fusiform Gyrus[a]	18	R	3	−84	−12	243	3.02
A1Loss	Inferior Frontal Gyrus/Insula	44	L	−45	27	−3	128	3.94
	Fusiform Gyrus/Lingual Gyrus	19	R	30	−81	−15	108	3.24
A2Win	Posterior Cingulate/Middle Occipital Gyrus/Culmen/Cuneus/Lingual Gyrus/Declive	30	L	−18	−66	3	1339	−4.95
	Lentiform Nucleus/Hypothalamus/Thalamus/Caudate/Culmen/Claustrum/Midbrain Red Nucleus/ Parahippocampal Gyrus/Putamen/ Ventral Striatum/vmPFC/Insula	—	R	27	12	−3	1475	−4.52
	Superior Occipital Gyrus/Precuneus/Inferior Parietal Lobule	19	R	48	−78	33	129	−4.24
	Middle Occipital Gyrus/Inferior Parietal Lobule/Supramarginal Gyrus/Middle Temporal Gyrus/ Superior Temporal Gyrus	18	R	33	−96	6	481	−4.19
	Cingulate Gyrus/Medial Frontal Gyrus/Superior Frontal Gyrus	31	R	15	−21	48	386	−3.98
	Insula/Superior Temporal Gyrus	13	R	45	−30	18	135	−3.97
	Inferior Parietal Lobule/Precuneus/Angular Gyrus	40	L	−33	−54	51	192	−3.63
	Precentral Gyrus/Inferior Frontal Gyrus	6	L	−60	3	30	97	−3.57
	Precentral Gyrus	4	L	−42	−12	63	92	−3.42
	Fusiform Gyrus/Culmen/Uvula/Declive	37	R	45	−51	−15	205	−3.27
A2Loss	Lingual Gyrus/Posterior Cingulate/Cuneus/Declive/Middle Temporal Gyrus/Culmen/ Parahippocampal Gyrus	18	L	−15	−69	−6	1161	−4.88
	Midbrain Red Nucleus/Thalamus/Lentiform Nucleus/Ventral Striatum/Caudate/Putamen/Midbrain Substantia Nigra/OFC	—	R	3	−15	−21	828	−4.82
	Inferior Parietal Lobule/Middle Occipital Gyrus/Cuneus/Precuneus/Superior Parietal Lobule	40	R	39	−48	54	532	−4.55
	Superior Temporal Gyrus/Middle Temporal Gyrus/Insula/Fusiform Gyrus	41	R	51	−30	12	313	−4.01
	Inferior Parietal Lobule/Precuneus	40	L	−36	−54	48	205	−3.98

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MIDT Phase	Structure	BA	Left/ Right	MNI Coordinates x	y	z	k	*T* Value
	Superior Frontal Gyrus/Inferior Frontal Gyrus/vmPFC/Anterior Cingulate/OFC	11	R	12	51	−24	143	−3.85
	Precentral Gyrus	6	L	−63	6	21	99	−3.81
	Cingulate Gyrus/Medial Frontal Gyrus	31	R	9	−9	51	96	−3.63
	Middle Occipital Gyrus/Cuneus	18	L	−33	−96	0	178	−3.52
	Precentral Gyrus/Postcentral Gyrus/Inferior Parietal Lobule	6	L	−45	−3	57	183	−3.51
OCWin	Precuneus/Lingual Gyrus/Caudate/Insula/Inferior Parietal Lobule/Middle Temporal Gyrus/Superior	31	L	−24	−72	15	2307	−4.98
	Temporal Gyrus/Parahippocampal Gyrus/Medial Frontal Gyrus/Cuneus/Inferior Frontal Gyrus/ Lentiform Nucleus/Ventral Striatum/Putamen/Caudate/Superior Temporal Gyrus/Claustrum/ Thalamus/Posterior Cingulate/Anterior Cingulate/Middle Frontal Gyrus/OFC/Cingulate Gyrus/ Hypothalamus/Inferior Frontal Gyrus	13	R	45	12	−6	605	−4.18
	Insula/Superior Temporal Gyrus/Precentral Gyrus/Inferior Parietal Lobule/Inferior Frontal Gyrus/ Caudate							
OCLoss	Inferior Occipital Gyrus/Middle Occipital Gyrus/Fusiform Gyrus/Inferior Temporal Gyrus	19	R	33	−72	−3	240	4.16
	Middle Occipital Gyrus/Inferior Occipital Gyrus	19	L	−36	−84	0	135	3.64
	Middle Temporal Gyrus/Superior Temporal Gyrus	21	L	−57	−48	3	137	3.57
	Parahippocampal Gyrus/Posterior Cingulate/Middle Temporal Gyrus	30	L	−24	−51	0	184	−3.66

A1Loss, prospect of loss phase; A1Win, prospect of reward phase; A2L, anticipation of loss; A2Win, anticipation of reward; BA, Brodmann area; k, voxel cluster size (each voxel = 3 mm^3); L, left; MIDT, Monetary Incentive Delay Task; MNI, Montreal Neurological Institute; OCLoss, notification of loss; OCWin, notification of reward; OFC, orbitofrontal cortex; R, right; vmPFC, ventromedial prefrontal cortex; other abbreviations as in Table 1.

[a]With a conservative Bonferroni-correction for multiple comparisons between different reward phases, these clusters do not survive correction.