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Prefrontal responses during proactive and reactive inhibition are differentially impacted by stress in anorexia and bulimia nervosa

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Conflicts of interest:

The authors declare no competing financial interests.
Abstract

Binge-eating is a distressing, transdiagnostic eating disorder symptom associated with impulsivity, particularly in negative mood states. Neuroimaging studies of bulimia nervosa (BN) report reduced activity in fronto-striatal regions implicated in self-regulatory control, and an influential theory posits that binge-eating results from self-regulation failures under stress. However, there is no direct evidence that psychological stress impairs self-regulation in binge-eating disorders, or that any such self-regulatory deficits generalize to binge-eating in underweight individuals (i.e., the anorexia nervosa bingeing/purging subtype; AN-BP). We therefore determined the effect of acute stress on inhibitory control in 85 women (33 BN, 22 AN-BP, 30 controls). Participants underwent repeated functional MRI scanning, during performance of the stop-signal anticipation task, a validated measure of proactive (i.e., anticipation of stopping) and reactive (outright stopping) inhibition. Neural and behavioral responses to induced stress and a control task were evaluated on two, consecutive days. Women with BN had reduced proactive inhibition while prefrontal responses were increased in both AN-BP and BN. Reactive inhibition was neurally and behaviorally intact in both diagnostic groups. Both AN-BP and BN groups showed distinct, stress-induced changes in inferior and superior frontal activity during both proactive and reactive inhibition. However, task performance was unaffected by stress. These results offer novel evidence of reduced proactive inhibition in BN, yet inhibitory control deficits did not generalize to AN-BP. Our findings identify intriguing alterations of stress responses and inhibitory function associated with binge-eating, but they counsel against stress-induced failures of inhibitory control as a comprehensive explanation for loss-of-control eating.

Significance statement:

Binge-eating is a common psychiatric syndrome that feels uncontrollable to the sufferer. Theoretically, it has been related to reduced self-regulation under stress, but there remains no direct evidence for this link in binge-eating disorders. Here, we examined how experimentally-induced stress affected response inhibition in controls and women with anorexia nervosa and bulimia nervosa. Participants underwent repeated brain scanning under stressful and neutral conditions. Although patient groups had intact action cancellation, slowing of motor responses was impaired in bulimia nervosa, even when the likelihood of having to stop increased. Stress altered brain responses for both forms of inhibition in both groups, yet performance remained unimpaired. These findings counsel against a simple model of stress-induced disinhibition as an adequate explanation for binge-eating.
1. Introduction

Anorexia Nervosa (AN) and Bulimia Nervosa (BN) are eating disorders (EDs) that share cardinal symptoms, including recurrent binge-eating and compensatory behaviors (e.g., vomiting). Binge-eating occurs in both BN and the binge-eating and purging subtype of AN (AN-BP; (American Psychiatric Association, 2013a)), and it engenders substantial distress and impairment (Udo & Grilo, 2018). Although binge-eating has been related to aberrant reward and self-regulatory processing (Berner & Marsh, 2014; Frank et al., 2011; Schienle et al., 2009), its pathophysiological correlates remain poorly characterized.

An influential model posits that binge-eating emerges following negative affective states, which reduce an individual’s capacity for self-control, thereby leading to loss-of-control eating (Heatherton & Baumeister, 1991). While elevated trait impulsivity in BN (Fischer et al., 2008) and AN-BP (Hoffman et al., 2012) lends support to this model, experimental studies of self-regulation are more equivocal due to inconsistencies across neural and behavioral findings (e.g., (Lock et al., 2011)). For example, fMRI studies of adolescent (Marsh et al., 2011) and adult (Marsh et al., 2009; Skunde et al., 2016) BN report reduced fronto-striatal activity during conflict and action inhibition trials on Simon Spatial and Go/NoGo tasks, respectively, yet behavioral impairments were only observed on the Simon Spatial task in adult BN. Altered brain activity without behavioral impairment could indicate either inefficient or compensatory neural responses to preserve task performance. Interestingly, despite unaffected stop-signal performance, augmented medial prefrontal and anterior cingulate cortex (ACC) activity on failed stop-signal trials has predicted the subsequent onset of ED behaviors (Bartholdy et al., 2019).

Inconsistencies across levels of analysis and cognitive tasks could partly reflect heterogeneity within the theoretical construct of ‘self-control.’ Behavioral and neurobiological data support related but dissociable forms of impulsivity, including temporal impulsivity and response inhibition, or ‘inhibitory control’, which is the capacity to slow or stop a response tendency (Dalley et al., 2011). As binge-eating episodes are characterised by a sense that one...
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cannot stop eating (i.e., an ongoing behavior), inhibitory control tasks perhaps best model this behavior. Theoretical frameworks suggest that inhibitory control is modulated by proactive (i.e., goal-directed preparation of stopping) and reactive (stimulus-driven action cancellation) processes (Aron, 2011), which have both shared and unique neural correlates. Bilateral frontoparietal and basal ganglia regions form a broad inhibitory control network that subserves both processes, but bilateral superior parietal and right-dominant, frontal, temporal and parietal regions have been uniquely related to proactive and reactive inhibition, respectively (van Belle et al., 2014; Zandbelt et al., 2013). Therefore, distinctions between proactive and reactive inhibition should be considered when interrogating self-regulatory impairment(s) associated with binge-EDs.

Finally, efforts to validate the model must consider the impact of mood states on self-regulatory control. Although momentary stress precedes binge-eating and purging in BN (Berg et al., 2013) and AN (Culbert et al., 2016), it is unknown if inhibitory control mediates this association. Acute stress increases palatable food preference among male dieters, which co-occurs with augmented fronto-limbic-striatal functional connectivity and reduced connectivity between the ventromedial and dorsolateral prefrontal cortex (dlPFC; (Maier et al., 2015)). Thus, stress may impair goal-directed, prefrontal control, instead evoking habitual responding to food. Indeed, stress-induced decreases in bilateral precuneus, ACC and dlPFC responses to palatable food cues in BN moderated the association between stress and binge-eating in daily life (Fischer et al., 2017).

Here, we investigated the effect of acute stress on two key inhibitory modes in women with AN-BP, BN and unaffected controls. Participants attended a two-day, inpatient study session, which included repeated fMRI scanning under neutral and stressful conditions. Patient groups were expected to have reduced reactive inhibition and inferior fronto-striatal activity at baseline, which would be exacerbated by acute stress. We predicted baseline proactive inhibition to be reduced in BN but augmented in AN-BP compared to controls, aligning with restrictive AN.
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(Bartholdy et al., 2017). However, both groups were expected to show stress-induced proactive inhibition impairments and correspondingly altered frontoparietal activity. Finally, exploratory analyses related inhibitory control measures to laboratory-based eating behavior.

1. Methods and Materials

2.1 Participants

We recruited eighty-five women (M±SD = 23.96 ± 3.98y) through posted advertisements, the B-eat charity and an adult ED service in Cambridgeshire. Eligible volunteers were aged 18 to 40 years, English-speaking, had normal or corrected-to-normal vision and, for patient groups, met DSM-5 diagnostic criteria for either AN-BP or BN. Healthy controls with a lifetime psychiatric disorder were ineligible. Patient volunteers with binge-eating disorder, neurodevelopmental disorders, lifetime serious mental illness (e.g., bipolar or psychotic disorders), and/or substance or alcohol use disorders (SUDs) in the past 6 months were excluded. For all groups, exclusion criteria included: left handedness, estimated IQ<80, body mass index (BMI)>29.9 kg/m², MRI contraindications (e.g., pregnancy, some metallic implants), metabolic, neurological or cardiovascular diseases (e.g., anemia), lactation, bariatric surgery, and high nicotine dependence, as per the Fagerström Test for Nicotine Dependence (FTND; (Heatherton et al., 1991)). While not an exclusion criterion for the study, all participants who were prescribed psychotropic medication reported taking a stable dose for at least two weeks prior to participation, aligning with recommendations of Frank et al. (2018). The study was approved by the Cambridge East Research Ethics Committee (Ref. 17/EE/0304), and all participants provided signed, informed consent.

Participants were matched on age, IQ and, for BN and HC groups, BMI (t(61)=0.19, p=.85; Table 1). Moreover, rates of binge-eating and purging, current treatment, comorbid psychopathology and medication use (Table 1-1) did not differ significantly between patient groups. All AN-BP participants reported recurrent objective binge-eating, and the majority (n=19) suffered with purging behaviors.
2.2 Study design

Participants underwent the same study procedure as described previously (Westwater et al., 2020) and in Figure 1A. Briefly, potential volunteers completed a telephone screening and self-report questionnaire of psychopathology symptoms (American Psychiatric Association, 2013b) prior to attending an outpatient screening session at Addenbrooke’s hospital, Cambridge, UK. One hundred eligible volunteers completed the outpatient screening session, where they provided informed consent and a fasting blood sample for assessment of full blood count and thyroid hormones. Then, participants’ height, weight and body composition (via dual-energy X-ray absorptiometry) were measured prior to a clinical assessment, in which the Eating Disorder Examination (v16; (Cooper & Fairburn, 1987)) and Structured Clinical Interview for DSM-5 (First et al., 2015) were administered to determine ED diagnoses and comorbid psychopathology, respectively. Participants also completed the National Adult Reading Test (Blair & Spreen, 1989) to determine their estimated IQ, and the FTND was used to assess nicotine dependence.

To reduce participant burden, patient participants who lived outside of Cambridgeshire (n=12) completed the screening session remotely. Participants who underwent remote screening completed all blood sampling and anthropometric measurements during the overnight study session.

Eighty-five women (n=22 AN-BP, n=33 BN, n=30 HC) were eligible for the two-day, overnight study session. Study sessions began at either 08.00 or 09.00h, and participants’ height and weight were measured prior to a standardized breakfast and a cognitive testing battery. Following a mid-morning snack, participants began a 6-hour fast. A cannula was placed approximately 1 hour prior to MRI scanning on Day 1, and blood samples for cortisol and gut hormones were acquired at fixed timepoints (Westwater et al., 2020). Participants began MRI scanning between 13.30 and 14.30h to control for diurnal fluctuations in cortisol. While scanning, participants performed the stop-signal anticipation task (SSAT; (Zandbelt & Vink,
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201  (2010)) twice, immediately pre- and post-manipulation, and manipulation order (stress vs. neutral) was counterbalanced across participants. Then, participants had an unsupervised ad libitum meal, and those who did not meet their estimated energy requirements were offered an evening snack. This free-choice meal simulated naturalistic circumstances under which participants who suffer with binge-eating would experience urges to binge, where stress-induced increases in consumption would lend support to theoretical models of binge-eating (Heatherton & Baumeister, 1991). The study protocol was identical on Day 2, and participants were discharged following the meal.

2.3 Stop-signal anticipation task

The SSAT measures both proactive and reactive inhibition. ‘Proactive inhibition’ describes a goal-directed process, elicited by predictive cues, which restrains actions in preparation for stopping. In contrast, ‘reactive inhibition’ is a stimulus-driven process, where a salient signal triggers action cancellation. Task stimuli were presented using Presentation software (v20; Neurobehavioral Systems), and code may be retrieved from: https://github.com/bramzandbelt/SSAT.

As described previously (Zandbelt & Vink, 2010) and in Figure 1C, a background of three horizontal lines was present throughout the task. On each trial, a bar moved at a constant speed from the bottom line, reaching the top line in 1000ms. The main task (i.e., Go-signal trials) involved stopping the moving bar as it reached the middle line by pressing a button with one’s right index finger, yielding a target response time of 800ms. On a minority of trials, stop-signals were presented, where the moving bar stopped automatically before reaching the middle line. Participants were instructed to withhold their response in the event of a stop-signal. The probability of a stop-signal occurring on a given trial ranged from 0-33% and was indicated by the color of the middle line (green = 0%, yellow = 17%, amber = 20%, orange = 25% and red = 33%).
The initial stop-signal onset time was set to 500ms (i.e., 300ms before the target response time) for each stop-signal probability level. Throughout the task, the stop-signal onset time was adjusted using a staircase procedure (with steps of 25ms) depending on stopping accuracy, ensuring roughly equal numbers of successful and failed stop-signal trials.

Trials were presented in either baseline or experimental ‘blocks’ that were comprised of 12 to 15 trials each. The inter-stimulus interval was 1000ms. During baseline blocks, participants responded to trials in which the stop-signal probability was 0%, as indicated by the green stop-signal probability cue. Experimental blocks were comprised of go-signal trials with a stop-signal probability >0% (i.e., non-green cues) and stop-signal trials (also non-green cues). Stop-signal trials occurred pseudorandomly throughout experimental blocks, and stop-signal probability level varied across trials. Distinct trial orders were used for pre- and post-induction runs to account for practice effects within each day, where the trial orders were the same across participants and scan sessions. Simulations to determine the optimal trial order indicated that correlations between the different model regressors were sufficiently weak to generate parameter estimates.

In total, the SSAT included 474 trials: 234 go-signal trials with a stop-signal probability of 0%, 180 go-signal trials with a stop-signal probability >0% (30 yellow, 48 amber, 54 orange, 48 red) and 60 stop-signal trials (6 yellow, 12 amber, 18 orange, 24 red). In other words, the proportion of stop-signal trials was 25%. Two, 24s rest blocks were presented after one-third and two-thirds of the trials had elapsed. The task duration was 16min 36s. Participants completed a behavioural practice session prior to fMRI scanning on Day 1, in which they were trained on the Go and Stop tasks. Participants were notified that it was equally important to stop the moving bar at the target and to withhold their response in the presence of a stop-signal. We informed participants that stop-signals would never occur on trials with green cues, and the likelihood of a stop-signal occurring was lowest on ‘yellow’ cue trials and highest on ‘red’ cue...
trials, increasing as the cue colour transitioned to red. On Day 2, participants were reminded of the task instructions prior to scanning.

### 2.4 Stress induction

To enable within-subject assessment of stress responses, participants completed either an acute, psychological stress induction or a control task (i.e., neutral condition) on each day. In each condition, participants solved multiple-choice, mental math problems of varying difficulty while in the MR scanner; however, participants were motivated to respond accurately in the stress induction, whereas performance was not evaluated during the control task. Moreover, incorrect responses elicited negative feedback (e.g., “Your performance is below average.”) in the stress task, and uncontrollability, a central aspect of psychological stress, was engendered through the delivery of mild electrical stimulation to the abdomen at variable frequencies and intensities. Importantly, subjective ratings of stimulation intensity, unpleasantness and pain did not differ significantly across groups, indicating that abdominal stimulation was suitable for ED participants (Figure 1B). Subjective stress ratings were collected immediately pre- and post-induction, and these served to validate the stress manipulation. As psychological stress is inherently grounded in one’s subjective experience of the stressor, self-report ratings were viewed as the primary index of stress rather than physiological correlates, which vary substantially across sexes (e.g. cortisol) and remain poorly characterized in women (Ali et al., 2020; Kajantie & Phillips, 2006). Details of the task structure have been described elsewhere (Westwater et al., 2020) and are summarized in following sections.

#### 2.4.1 Electrical stimulation

Throughout each task, ‘physical distractors’ were delivered to the abdomen in the form of mild electrical stimulation, using a DS7A constant current stimulator (Digitimer, UK). Before MRI scanning, the intensity of electrical stimulation was calibrated for each participant to account for inter-individual variability in shock tolerance. Two BIOPAC radio translucent electrodes (EL509) were filled with isotonic paste (GEL101) and positioned to the right of the
subject’s navel, between dermatomes T10 and T12. During the calibration procedure, participants indicated (1) when the stimulation was detectable but not uncomfortable, corresponding to pain ratings of 0 – 2, and (2) when the stimulation first became uncomfortable but not painful (pain ratings of 5 – 7, where 0 = no pain, 10 = very painful). Each shock pulse lasted 500μs.

For the stress induction, shocks were delivered in 5 – 20 pulse sequences with an interpulse interval range of 0.1 – 1s and an inter-train interval range of 0.1 – 3.9s, which were randomly sampled in MATLAB (v2017b; The Mathworks). Shock intensity was manually adjusted between the participant’s two threshold values throughout the induction. For the control task, stimulation was delivered at predictable intervals and a constant intensity, corresponding to the participant’s detection threshold. Trains consisting of 5 pulses were delivered at an interpulse interval of 0.55s with an inter-train interval of 2s. Shock delivery was not contingent on performance. We instructed participants to verbally communicate if the stimulation became painful at any time, in which case it would be reduced. No participants reported discomfort during the tasks, and subjective ratings of the stimulation were acquired immediately following the task.

2.4.2 Mental arithmetic control and stress task

Math task stimuli were presented in MATLAB, using Psychophysics Toolbox (v3; Brainard, 1997)), and code is available at: https://github.com/mwestwater/STRIvE-ED. On each day, participants completed 25 practice problems of variable difficulty, and they were instructed to try their best to select the correct answer without taking too much time. Stimuli were presented for a maximum of 30s, and participants had to respond by selecting one of the 3 choices. Feedback was presented for 2500ms either 500ms after the response, or after the 30s period elapsed. The next trial was presented following a variable interval (500 – 2500ms, jitter = 100ms).
Both the stress induction and control task included 48 multiple-choice mental arithmetic problems, which were matched on difficulty. Prior to the stress induction, participants were encouraged to respond accurately, and they were informed that only data from participants whose performance met the average group accuracy could be used in the study. Additionally, they were told that ‘physical distractors’ would be delivered to their abdomen, and that they would be monitored on a live video feed to check that they were paying attention to the task. Conversely, prior to the control task, participants were told that their performance would not be evaluated and that they would not be watched. Both tasks had the same trial structure as the practice task; however, for the stress induction, the initial stimulus presentation and response time (30s in the practice task) was set to 10% less than the participant’s average response time on the practice task. Accurate responses on 3 consecutive trials shortened the maximal response window by 10% to ensure low performance. As the sliding response window reduced the overall task duration, the ITI was set to 6s on every 6th trial to ensure that the task was sufficiently long for the stress induction to be effective. Participants received negative feedback to nonresponses and incorrect responses, whereas no feedback was provided for correct responses. At the end of the task, participants were informed that their performance did not meet the group average. For the control task, the stimulus presentation and response time was 30s on each trial, and feedback was only provided to indicate correct responses.

2.5 Image acquisition

MR scanning was completed at the Wolfson Brain Imaging Centre at Addenbrooke’s hospital on a 3T Siemens Skyra® scanner (Erlangen, Germany), fitted with a 32-channel, GRAPPA parallel-imaging head coil. On each day, 1.0mm isotropic T1-weighted structural images were acquired (TE=2.95ms, TR=2300ms, flip angle=9°, acquisition matrix=256 X 256mm). Echo-planar images were acquired across 30 interleaved slices with the following parameters: TR=1600ms, TE=23ms, flip angle=78°, acquisition matrix=64x64, 3.0 mm isotropic
voxels, 631 volumes. One participant was excluded for an incidental finding of white matter abnormalities, and this participant was followed up clinically.

2.6 Data analysis – SSAT performance

We assessed proactive inhibition by examining the effect of stop-signal probability on response time (RT), where participants tend to slow responding as the likelihood of having to stop increases (Verbruggen & Logan, 2009a; Vink et al., 2005, 2006; Zandbelt & Vink, 2010). Impaired proactive inhibition would be evident in a failure to increase RT when stop-signal probability increases, as this would suggest weaker anticipation of stopping. Reactive inhibition was indexed as stop-signal reaction time (SSRT), which represents the latency of the inhibition process. SSRT was computed using the integration method (Verbruggen & Logan, 2009b) across all stop-signal probability levels with go omission replacement (Verbruggen et al., 2019). Slower SSRTs would reflect greater latency of the inhibitory process and therefore impaired reactive inhibition.

Behavioral data were analyzed in R (R Core Team, 2015). Aligning with previous reports (Zandbelt et al., 2011; Zandbelt & Vink, 2010), go-signal RTs that were more than 1.5 times the interquartile range below the 25th percentile or above the 75th percentile of the RT distribution at each probability level, as well as on failed stop-signal trials, were defined as outliers. To minimize positive skew, a rank based inverse normal transformation was applied to RTs (R package RNOmni (McCaw, 2019)) prior to analysis. Analyses of proactive inhibition (trial RT) and reactive inhibition (SSRT) were conducted using the linear mixed-effects modelling (LMM) R package nlme (Pinheiro et al., 2016), where fixed effects of group, condition and time were included in both models, with random intercepts for within-subject variables nested within the subject’s random effect. Additionally, fixed and random effects for probability level (linear and quadratic terms) were included in the proactive inhibition LMM. Group differences were tested via non-orthogonal contrasts, comparing each patient group to controls, and model results are
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reported accordingly. Normality of the model residuals was determined by visual inspection of quantile-quantile plots.

2.7 Data analysis – fMRI

Image data were pre-processed and analyzed using FreeSurfer (v 6.0; (Dale et al., 1999; Fischl et al., 1999)) and AFNI software (Cox, 1996). For each subject, anatomical scans were co-registered with a linear transformation (AFNI program 3dAllineate) and averaged across days via 3dMean. The averaged structural image was then processed with the standard FreeSurfer recon-all pipeline. The resulting white matter and ventricle segmentations were resampled to 3mm isotropic resolution and eroded by 1 voxel along each axis. Remaining pre-processing steps were completed with the afni_proc.py python script, in which functional images were slice-time corrected, re-aligned to the minimum outlier functional volume, co-registered to the subject’s skull-stripped averaged anatomical image, non-linearly warped to the MNI152_T1_2009c template and smoothed using a 6mm full-width at half-maximum (FWHM) kernel. The first three principle components from the time series of lateral, third and fourth ventricle sources were estimated and regressed from functional volumes, along with six head motion parameters and their first-order derivatives. Local white matter was regressed from functional volumes using the fast ANATICOR pipeline (Jo et al., 2010). Functional volumes with a Euclidean norm motion derivative >0.5mm were censored, and participants with >10% of volumes censored were excluded from group-level analysis.

Functional MRI data from pre-stress, post-stress, pre-neutral and post-neutral sessions were available from n=84, n=79, n=80 and n=81 participants, respectively. One participant was excluded from analysis due to white matter abnormalities. In addition, 5 post-stress, 4 pre-neutral and 2 post-neutral runs were excluded because of excessive head motion. A technical error resulted in the exclusion of one additional post-neutral session. During a pre-neutral session, EPI acquisition had to be stopped due to a technical error; however, as ~70% of...
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functional volumes had been acquired for this participant, their pre-neutral run was included in the group-level analysis.

Statistical analysis followed a two-level procedure, where successful stop-signal trials, failed stop-signal trials, go-signal trials with non-0% stop-signal probability were modelled as regressors of interest in the first-level general linear models. In line with previous work (Zandbelt et al., 2011; Zandbelt & Vink, 2010), we included two amplitude modulators, RT and stop-signal probability level, for go-signal trials. AFNI models one regressor for the constant magnitude of the blood oxygenation-dependent (BOLD) response and separate regressors for each amplitude per time point unlike other packages that partition the variance of regressors sequentially. However, as RT (in this context, a measure of the tendency to withhold a response) and stop-signal probability contrasts may provide complementary information, both were used as measures of proactive inhibition. In addition, incorrect go-signal trials and rest blocks were included as nuisance regressors; go-signal trials with a stop-signal probability of 0% were not modelled, thus constituting an implicit baseline. Regressors were created by convolving gamma functions coding for response onset (or stop-signal delay for successful stop-signal trials) with a canonical hemodynamic response function. Within each subject run, we computed four contrast images: 1) the parametric effect of RT on go-signal activation (proactive inhibition), 2) the parametric effect of stop-signal probability on go-signal activation (proactive inhibition), 3) successful stop versus failed stop-signal trials (reactive inhibition) and 4) successful stop versus go-signal trials with 0% stop-signal probability (reactive inhibition). We generated two contrasts for reactive inhibition as there is no consensus on which contrast is most appropriate when investigating this inhibitory mode. Beta estimates were determined using restricted maximum likelihood estimation.

We conducted two group analyses for each contrast. First, we examined associations between diagnostic group (AnvHC and BNvHC), condition (stress vs. neutral), time (pre vs. post) and their interaction and the BOLD response in seven predefined regions of interest.
403 (ROIs; Figure 2A). A priori ROI selection was based on findings from previous functional
404 imaging studies of the SSAT (Zandbelt et al., 2011; Zandbelt & Vink, 2010), proactive and
405 reactive inhibitory control networks (van Belle et al., 2014), and NeuroSynth
406 (https://neurosynth.org) clusters associated with “stop signal” and “response inhibition” terms.
407 Averaged beta estimates were extracted from each ROI, as it was defined anatomically in the
408 Brainnetome atlas (Fan et al., 2016), using 3dmaskave. For each ROI, main and interaction
409 effects were tested in a LMM, and random intercepts for condition and time were included within
410 the random effect of the individual. As seven ROIs were tested per contrast, our alpha threshold
411 was reduced to p=.05/7=.007.
412
413 Next, we examined whether a group-by-time-by-condition interaction related to
414 differences in whole-brain activation. Whole brain analyses were completed using the linear-
415 mixed effects modelling AFNI program, 3dLME (Chen et al., 2013), where general linear tests
416 were implemented to test a priori contrasts of interest (e.g., AN>HC, BN>HC, stress>neutral,
417 post>pre). As the model tested a three-way interaction (AN>HC*stress>neutral*post>pre),
418 lower-order interaction and main effects were also included. Both F- and Z-statistics are
419 reported for each effect. Resulting group-level statistical maps were tested for significance using
420 cluster-level inference (cluster-defining threshold of p<.001, k=18.8, cluster probability of p<.05,
421 family wise error-corrected). Updated versions of 3dFWHMx and 3dClustSim were used to
422 correct for multiple comparisons, as these programs incorporate a mixed autocorrelation
423 function to model non-Gaussian noise structure and reduce false-positive rates (Cox et al.,
424 2017; Eklund et al., 2016). For visualization, the mean percent signal change was extracted
425 from significant whole-brain clusters using 3Dmaskave.

2.7 Exploratory analysis of inhibitory control and ad libitum consumption

We used LMMs to test whether SSRT, Barratt Impulsiveness scores (BIS-11; 48) or
brain regions implicated in the fMRI analyses explained variance in subsequent food intake
(kilocalories). As described previously (Westwater et al., 2020), one participant declined to
initiate the ad libitum meal on Day 2, and another reported severe nausea prior to the meal. We therefore modelled observations from 83 participants for these exploratory analyses. For consistency, SSRT and neural responses were modelled from post-manipulation runs only.

Each model included fixed effects of group (AnvHC and BNvHC), condition and impulsivity measure, where random intercepts for within-subject variables were included within the subject’s random effect. Models of SSRT and brain responses also included a person-centered random slope for these variables. Exploratory results were considered statistically significant at $p=.05$.

3. Results

3.1 Behavioral

3.1.1 Manipulation check

As previously reported (Westwater et al., 2020), both subjective stress (Figure 1B) and negative affect were significantly increased following the stress induction relative to the control condition. Moreover, a group-by-condition interaction identified stress-induced plasma cortisol decreases in BN, but not AN-BP, compared to controls (Figure 1-1; see (Westwater et al., 2020) for full details), aligning with previous reports of blunted stress responses in this disorder (Ginty et al., 2012; Monteleone et al., 2011; Pirke et al., 1992).

3.1.2 Reduced proactive inhibition in bulimia nervosa

We anticipated proactive inhibition would be impaired in BN and augmented in AN-BP while stress-induced impairments would be observed in both groups. RT increased with greater stop-signal probability ($\beta=0.01$, $t(1019)=13.08$, $p<.0001$); however, this effect was nonlinear, as a significant quadratic probability term suggested that RT slowing plateaued with increasing stop-signal probability ($\beta=-5.07$, $t(57919)=-5.28$, $p<.0001$). RT on non-0% go-signal trials was significantly decreased post-manipulation (i.e., at time 2; $\beta=-0.14$, $t(169)=-8.49$, $p<.0001$), which is consistent with the expected practice effects within each scanning session. Moreover, a significant group-by-probability interaction indicated poorer proactive inhibition in the BN group.
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455 relative to controls ($\beta=-6.54$, $t(1012)=-2.97$, $p=.003$; Figure 4A), where women with BN
456 demonstrated a smaller increase in RT relative to increasing stop-signal probability. The
457 addition of higher-order interaction terms did not significantly improve model fit ($\chi^2(13)=16.11$,
458 $p=.19$), indicating that proactive inhibition was not significantly affected by acute stress. RT on
459 0% stop-signal probability trials did not differ between AN ($p=.37$) or BN ($p=.96$) and control
460 participants, indicating equivalent performance on the baseline response task (Table 2).

3.1.3 No effect of patient group or stress on reactive inhibition

We predicted that both AN-BP and BN groups would demonstrate impaired reactive
inhibition relative to controls following the acute stress induction. The significant main effect of
462 time indicated that SSRT was reduced post-manipulation ($\beta=-3.29$, $t(166)=-3.23$, $p=.002$).
463 However, all other main and interaction effects on SSRT were nonsignificant (all $p's>.05$; Table
466 2). Data met the assumptions of the race model, as evidenced by faster RTs on failed stop-
467 signal trials compared to go-signal trials where stop-signals could occur ($\beta=-21.5$, $t(339)=-39.4$,
468 $p<.0001$).

3.2 Functional MRI

3.2.1 Proactive inhibition.

Examination of the parametric effects of stop-signal probability and RT identified
increased neural responses across frontoparietal regions that comprise the proactive inhibition
473 network (Figure 3A-B; see also Figures 3-1 and 3-2), indicating successful experimental
474 manipulation of proactive inhibition.

ROI analyses. Increasing stop-signal probability was associated with greater right
475 inferior frontal gyrus activity in the AN-BP group relative to controls ($\beta=0.007$, $t(81)=2.91$,
476 $p=.005$; Figure 2B). IFG activity decreased post-manipulation (i.e., at time 2) across all groups
477 ($\beta=-0.006$, $t(156)=-3.20$, $p=.002$). In addition, the parametric effect of RT on left premotor cortex
479 activity was related to a three-way interaction, where the BOLD response decreased in BN
480 relative to controls following the stress induction ($\beta=-0.62$, $t(151)=-3.48$, $p<.001$; Figure 2C).
Whole-brain analyses. Increasing RT was related to reduced left supplementary motor area (SMA) activity post-manipulation (Figure 4-1). Moreover, the effect of stop-signal probability was significantly affected by time, where activity across the proactive inhibition network generally decreased post-manipulation (Figure 4-1). In line with behavioral findings, the effect of stop-signal probability also differed significantly by group, where the parameter was related to increased activity in the left superior frontal gyrus (SFG) in BN relative to controls (k=25 voxels, Z=4.58; Figure 4B & Figure 4-1). A significant three-way interaction was associated with right SFG activity (k=19 voxels, F(2,231)=10.77). As this effect was not captured by our a priori contrasts, we conducted an additional general linear test, which examined the three-way interaction in BN versus AN-BP. This test indicated augmented SFG activity in BN relative to AN-BP following stress (k=34 voxels, Z=4.52; Figure 4C & Figure 4-1) as patient groups had opposing functional responses to stress in this cluster.

3.2.2 Reactive inhibition.

Analyses of reactive inhibition (Stop>Go-signal and Stop>FailedStop trials) indicated increased neural responses across the inhibitory control network (Figure 3C & D; see also Figures 3-3 & 3-4) with markedly similar activation patterns across groups.

ROI analyses. The main effect of group and all interaction effects were nonsignificant across all ROIs for both reactive inhibition contrasts. A significant main effect of time was related to right pre-supplementary motor cortex ($\beta$=-0.02, t(156)=-3.51, p<.001), ACC ($\beta$=-0.01, t(156)=-2.79, p=.006) and bilateral superior parietal cortex activity ($\beta$=-0.02, t(156)=-4.46, p<.001) on Stop>Go-signal trials, where activity declined post-manipulation. Moreover, the main effects of condition ($\beta$=0.01, t(82)=2.77, p=.007) and time ($\beta$=0.01, t(156)=3.14, p=.002) were associated with ACC activity during Stop>FailedStop trials, where deactivation was less negative on the stress day and post-manipulation (i.e., at time 2). As a time-by-condition interaction term was not significantly related to ACC activity, the observed differences likely reflect BOLD variability across scan days that was not specific to the stress induction.
Whole-brain analyses. On Stop>Go-signal trials, neural responses were significantly reduced across the inhibitory control network post-manipulation (Figure 5-1). Activity in left middle temporal, thalamic, posterior insular, occipital and inferior frontal clusters was reduced post-manipulation during Stop>FailedStop trials. Moreover, left precentral gyrus activity on Stop>FailedStop trials was increased on the stress day relative to the neutral day. Finally, a three-way interaction indicated reduced activity in the right vmPFC during reactive inhibition (Stop>FailedStop trials) in AN-BP relative to controls following stress (k=32 voxels, Z=-4.19; Figure 5).

3.2.3 Associations with food intake

We previously reported that AN-BP and BN groups consumed less in the buffet (Figure 6-1) than controls, and intake was unaffected by stress (Westwater et al., 2020). On the stress day, women with AN-BP, BN and control groups consumed M(SD)=898(872), 873(409) and 1099(335) kilocalories, respectively. AN-BP, BN and control groups ate M(SD)=849(806), 941(560) and 1129(294) kilocalories, respectively, on the neutral day.

Here, we examined whether brain regions demonstrating differing neural responses between groups (e.g., left premotor cortex, right IFG, left SFG) or in a group-by-condition-by-time interaction (right SFG, right vmPFC) explained variance in food intake. Left SFG responses during proactive inhibition predicted increased kilocalorie intake (Z-scored; $\beta=3.56$, t(71)=2.38, p=.02), and vmPFC responses during reactive inhibition were negatively related to consumption ($\beta=-0.81$, t(71)=-2.85, p=.006; Figure 6). These associations were observed in the full sample and did not differ significantly by group or condition. The effects of SSRT, trait impulsivity and all interaction terms were nonsignificant (all p’s>.05).

2. Discussion

As failed self-regulation in response to stressors has gained traction as a putative mechanism of binge-eating, it has become increasingly important to characterize the precise self-regulatory deficits associated with binge-eating disorders. We assessed the impact of.
induced stress on inhibitory control in women with AN-BP, BN and matched controls, reporting three key findings. First, women with BN, but not AN-BP, had reduced proactive inhibition, yet both groups demonstrated increased prefrontal responses during the anticipation of stopping compared to controls. Second, we found stress-induced changes in the neural correlates of proactive and reactive inhibition, with notable differences across diagnostic groups. Third, AN-BP and BN groups had intact reactive inhibition, and neither proactive nor reactive inhibition performance was affected by acute stress.

We report novel evidence of reduced proactive inhibition in BN relative to controls, which co-occurred with increased activity in the left dorsolateral SFG. Increased left SFG activity and concurrent performance deficits could reflect inefficient recruitment of other regions within the inhibitory control network, namely inferior and middle frontal gyri, which share reciprocal connections with the SFG (W. Li et al., 2013). Inefficient or compensatory responses may also explain increased right IFG responses in AN-BP during intact proactive inhibition. Alternatively, given the role of the pars opercularis in ‘braking’ motor responses (Aron et al., 2014; Swann et al., 2012), increased activity could reflect improved proactive adjusting in AN-BP on the neural level, complementing previous behavioral reports in AN-R (Bartholdy et al., 2017). Exploratory analyses found that left SFG responses predicted increased post-scan calorie intake. This finding lends additional support to the notion of inefficiencies across the proactive inhibitory network that may relate to abnormal eating behavior, specifically overconsumption. As this association was not moderated by disorder status, this finding might suggest a general—rather than diagnosis-specific—association between left SFG activation during proactive inhibition and food intake. However, our sample may have lacked sufficient statistical power to detect small, interaction effects, and future studies with larger sample sizes will be critical to determining if and how this relationship differs between AN-BP, BN and control groups.

Acute, psychological stress altered right SFG and left premotor cortex responses during proactive inhibition, as well as right vmPFC activity during outright stopping, differently between...
Specifically, stress augmented right SFG responses to increasing stop-signal probability in BN relative to AN-BP. In BN, these stress-induced increases in SFG responses perhaps compensated for concomitant decreases in premotor activity during RT slowing, thus preserving task performance. Indeed, increased prefrontal activity has been reported in healthy adults following pain stress, where activation was presumed to support working memory performance (Porcelli et al., 2008).

One explanation for reduced, post-stress vmPFC responses in AN-BP relative to controls, who showed augmented responses, could be stress-induced alterations in inter-regional modulation (Veer et al., 2011). The vmPFC is the primary cortical target of limbic projections (Averbeck & Seo, 2008), and stress-induced increases in activity may provide top-down modulation of amygdala reactivity and negative emotions. While not typically associated with inhibitory control, augmented vmPFC activity during reactive inhibition has been reported following methylphenidate administration (C.-S. R. Li et al., 2010) and neuromodulation of the pre-SMA (Yu et al., 2015). These findings, together with our observations following acute stress, could implicate norepinephrine signaling in altered vmPFC activation, but further research is needed. Our finding of a negative relationship between vmPFC responses to reactive stopping and post-scan calorie consumption suggests that vmPFC activation during inhibition may be important for dietary control. However, as discussed above, the specificity of this brain-behavior association to clinically-significant eating pathology remains unclear, and we encourage future replication attempts in larger sample sizes.

Stress-induced reductions in prefrontal responses during both proactive and reactive inhibition in AN-BP could reflect the consequences of prolonged, extreme stress, namely significantly low weight, which engenders various cognitive and neuroendocrine perturbations (Delvenne et al., 1995; Misra & Klibanski, 2014). Interestingly, preclinical research has identified disrupted dopaminergic signaling following severe stress (Hollon et al., 2015; Lemos et al., 2012); however, the effect of stress on dopaminergic projections to prefrontal cortex remains
understudied. The dearth of research in this area discourages a premature interpretation of our stress induction effects in AN-BP. Instead, findings of task-specific, stress-induced reductions in prefrontal responses in AN-BP may inform future investigations into neurocognitive alterations associated with prolonged and increasing stress.

Contrary to our hypotheses, reactive inhibition, indexed as SSRT, was unaffected by diagnostic group or stress, and it was unrelated to free-choice consumption. As we have reviewed, findings of impaired self-regulatory performance in BN and AN-BP are inconsistent (Marsh et al., 2011; Skunde et al., 2016), and our results suggest that the subjective ‘loss of control’ that characterizes binge-eating episodes does not relate to deficits in one’s capacity for action cancellation. While often considered a valid and translational measure of inhibitory control, our findings, and a recent mega-analysis of polysubstance use, question the clinical utility of SSRT. Indeed, the latter found that increased SSRT was not significantly related to various SUDs, including alcohol and cocaine use disorders (Liu et al., 2019). As stress-induced deficits in the ability to delay food reward were found in non-clinical samples (Maier et al., 2015), future research should assess state changes in decision-making as a potential mechanism of loss-of-control eating in clinical groups.

Although our design had notable strengths, several limitations should be considered. First, we recruited a representative sample of women with EDs, and as expected, the majority suffered with comorbid psychopathology and many used medication. It is difficult to robustly adjust for these in analyses as our modest sample size would render any subgroup analysis of medication- or comorbidity-free participants very underpowered. However, these characteristics may improve the generalizability of our findings as comorbidity and medication use are the norm rather than the exception amongst individuals with EDs (Fazeli et al., 2012; Udo & Grilo, 2019). Indeed, rates of psychiatric comorbidity (73% AN-BP, 70% BN) and medication use (46% AN-BP, 30% BN) in our sample align with those reported in epidemiological studies of EDs (Fazeli et al., 2012; Ulfvebrand et al., 2015). One concern with medication use is a potential impact on
response inhibition. Of those using medication, most were prescribed either selective serotonin
reuptake inhibitors or serotonin-norepinephrine reuptake inhibitors with high affinity for 5-HT,
and 5-HT modulation has been shown to have no effect on response inhibition (Chamberlain et
al., 2006). Nevertheless, future studies could attempt to dissociate medication effects by
including an unmedicated, positive control group, but such a group would likely differ from the
experimental group in other important ways, such as illness severity and treatment duration.
Second, despite providing increased statistical power, repeated-measures designs may elicit
practice effects. While our design mitigated these effects through counterbalancing, repeated
performance of the SSAT on each day could induce within-session training effects. However,
pre- and post-induction task performance militated against the possibility that baseline, non-
specific performance differences across the groups could contaminate our results. Moreover, as
within-session repetition occurred across both conditions, we are confident that our significant
results are specific to induced stress when accounting for potential practice effects. Third,
disorder-salient stimuli (e.g., food), which may accentuate or reveal self-regulatory deficits (Wu
et al., 2013), were not used, and future study should examine the impact of stress on
performance in these contexts. Finally, the conditions under which stress was induced (i.e., in
an MR scanner) and eating behavior was assessed differed from those in daily life, and
integration of neuroimaging with prospective, real-world monitoring of internal states and binge-
eating behavior would extend our work.

Our findings counsel against a simplistic, stress-induced failure of regulation as an
overall explanation for binge-eating in AN-BP and BN, underscoring the need for alternative
models of these illnesses. Moreover, dissociations across diagnostic groups suggest that
models of binge-eating based on BN may not apply to AN-BP. Given the complex metabolic and
psychological disturbances associated with these disorders, future efforts to identify the
neurocognitive mechanisms of binge-eating should consider the roles of interacting peripheral
physiological processes.
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### Table 1. Clinical and demographic information

| Characteristic                  | AN (n = 22) | BN (n = 33) | HC (n = 30) | Analysis |
|---------------------------------|-------------|-------------|-------------|----------|
|                                | M          | SD          | M          | SD       | M        | SD       | χ²(df), F(df), W, t(df) | p       |
| Age (y)                         | 24.6       | 4.7         | 23.6       | 3.9      | 23.9     | 3.5      | X²(2) = 0.8          | .69     |
| BMI (kg/m²)                     | 16.4       | 1.4         | 22.0       | 2.4      | 21.9     | 2.1      | X²(2) = 48.4         | <.001   |
| IQ a                            | 116        | 5           | 114        | 5        | 114      | 5        | X²(2) = 3.2          | .21     |
| Age of onset (y)                | 15.6       | 2.4         | 16.2       | 3.1      | -        | -        | t(51.8) = -0.8       | .42     |
| Illness duration (y)            | 9.0        | 5.8         | 7.4        | 4.0      | -        | -        | t(34.4) = 1.1        | .27     |
| Beck Depression Inventory       | 35.3       | 12.0        | 32.7       | 10.5     | 2.4      | 2.8      | X²(2) = 57.7         | <.001   |
| Trait Anxiety Inventory         | 63.1       | 10.4        | 62.8       | 7.3      | 33.0     | 6.9      | F(2) = 151.1         | <.001   |
| Barratt Impulsiveness Scale     | 66.2       | 14.0        | 68.4       | 11.1     | 56.7     | 6.3      | F(2) = 10.4         | <.001   |
| Eating Disorder Examination     | 4.4        | 0.8         | 4.6        | 0.8      | 0.2      | 0.2      | X²(2) = 58.0         | <.001   |
| Eating Disorder Examination     |            |             |            |          |          |          |                     |         |
| Objective binge-eating episodes  | 38.1       | 47.9        | 23.0       | 29.1     | -        | -        | W = 317.5            | .43     |
| Subjective binge-eating episodes| 9.5        | 12.8        | 6.6        | 6.2      | -        | -        | W = 341.5            | .93     |
| Vomiting episodes               | 43.5       | 51.6        | 24.2       | 31.0     | -        | -        | W = 304.0            | .31     |
| Laxative episodes               | 1.1        | 3.4         | 2.0        | 3.9      | -        | -        | W = 421.5            | .18     |
| Exercise episodes               | 7.4        | 13.6        | 10.9       | 9.4      | -        | -        | W = 478.5            | .04     |
| Comorbid diagnoses              |            |             |            |          |          |          |                     |         |
| Anxiety disorder                | 3          | 13.6        | 3          | 9.1      | -        | -        | X²(1) = 0.3          | .69     |
| Major depressive episode        | 15         | 68.2        | 16         | 48.5     | -        | -        | X²(1) = 2.1          | .15     |
| Personality disorder            | 2          | 9.1         | 5          | 15.2     | -        | -        | X²(1) = 0.4          | .69     |
| Any current treatment           | 13         | 59.0        | 15         | 45.5     | -        | -        | X²(1) = 1.0          | .32     |
| Psychotherapy                   | 9          | 40.9        | 9          | 27.3     | -        | -        | X²(1) = 1.1          | .29     |
| Medication                      | 10         | 45.5        | 10         | 30.3     | -        | -        | X²(1) = 1.3          | .25     |
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| Prior restrictive AN | 14 | 63.6 | 10 | 30.3 | - | - | $\chi^2(1) = 6.0$ | .01 |

Note: aEstimated full-scale IQ from the National Adult Reading Test. bEDE ratings reflect counts over the previous 28 days. Group differences were evaluated using one-way ANOVA and, for non-normally distributed data, the nonparametric Kruskal-Wallis test. The two-samples t-test (two-sided), Mann-Whitney U test and chi-square test were used to assess differences between AN and BN groups. See Table 1-1 for type and dose of prescribed medications.
**Table 2.** SSAT performance metrics by group and condition

| Measure       | Group | Pre M ± 95% CI | Post M ± 95% CI | Stress Pre M ± 95% CI | Stress Post M ± 95% CI |
|---------------|-------|----------------|-----------------|-----------------------|------------------------|
| SSRT (ms)     | AN    | 273 ± 5        | 269 ± 7         | 278 ± 5               | 268 ± 5                |
|               | BN    | 271 ± 5        | 268 ± 5         | 270 ± 5               | 270 ± 5                |
|               | HC    | 270 ± 6        | 268 ± 4         | 271 ± 5               | 267 ± 4                |
| Go Trial 0% (ms) | AN  | 814.4 ± 1.1    | 808.7 ± 1.1     | 818.5 ± 1.2           | 813.2 ± 1.1            |
|               | BN    | 820.7 ± 1.0    | 815.0 ± 0.9     | 821.0 ± 1.0           | 816.7 ± 0.9            |
|               | HC    | 823.6 ± 1.1    | 817.7 ± 1.0     | 818.9 ± 1.1           | 814.4 ± 1.0            |
| Stop accuracy (%) | AN  | 58.7 (4.1)     | 57.7 (4.7)      | 58.6 (4.2)            | 58.8 (3.7)             |
|               | BN    | 60.2 (5.2)     | 59.3 (6.0)      | 60.1 (5.2)            | 58.6 (4.2)             |
|               | HC    | 59.5 (4.7)     | 59.1 (5.4)      | 57.5 (5.1)            | 57.7 (4.7)             |
| Accuracy (%)  | AN    | 98.3 (3.8)     | 99.1 (0.9)      | 98.0 (1.9)            | 99.2 (0.9)             |
|               | BN    | 98.7 (1.3)     | 98.9 (1.9)      | 97.4 (5.7)            | 99.4 (0.7)             |
|               | HC    | 98.0 (3.3)     | 99.3 (0.9)      | 98.4 (1.7)            | 99.3 (0.9)             |

Note: ‘Accuracy’ represents the percentage of go-signal trials on which participants made a response.
Figure 1. Overview of study design and stop-signal anticipation task

A) Diagram of inpatient study protocol with representative timeline. Participants were randomized to either a stress induction or control task on each day, which was completed in the MR scanner. Created with BioRender.com. See Figure 1-1 for plasma cortisol responses (% change from baseline) to the stress and control tasks. B) Participant ratings of subjective stress and electrical stimulation. The stress manipulation induced a significantly greater change in subjective stress compared to the neutral task. Participants rated the electrical stimulation as more painful, intense and unpleasant following stress as compared to the control task, where stimulation was intended to be detectable but not unpleasant (see Westwater et al., 2020). Ratings did not differ significantly by group (all p’s >.05). Error bars = SEM. C) Schematic of SSAT trial types adapted from Zandbelt & Vink (2010). Left: On go-signal trials, participants were instructed respond when a moving bar reached the middle line. The target response time was 800ms on each 1000ms trial (1000ms inter-trial interval). Middle: A minority of trials (25%) were stop-signal trials, where the moving bar stopped automatically before reaching the middle line. Participants were instructed to withhold their response in the event of a stop-signal. Right: To index proactive inhibition, the probability of a stop-signal occurring on a given trial ranged from 0 – 33%, as indicated by colored cues. Participants were told that stop-signals would never occur on “green” (baseline) trials, but the likelihood of a stop-signal occurring increased across yellow to red trials.
Figure 2. Region of interest analyses identify altered inferior frontal and premotor activity during proactive inhibition in anorexia and bulimia nervosa. A) ROI analyses were conducted in seven regions that have previously been associated with proactive and reactive inhibition (van Belle et al., 2014; Zandbelt et al., 2011): right putamen (1), right opercular inferior frontal gyrus (2), right ventral inferior frontal gyrus (3), bilateral pregenual anterior cingulate cortex (4), bilateral caudate (5), bilateral superior parietal cortices (6), left premotor cortex (7) and right pre-supplementary motor cortex (8). Blue regions were used in analysis of both proactive and reactive inhibition, whereas pink and red regions were unique to proactive and reactive analyses, respectively. ROIs are displayed in neurological orientation (L=left). B) The parametric effect of stop-signal probability was related to increased right inferior frontal gyrus (pars opercularis) activity in AN-BP relative to controls (p=.005). C) A three-way interaction indicated that the parametric effect of reaction time was related to decreased left premotor activity in BN compared to controls in following the stress induction (p<.001).
Figure 3. Whole-brain activation in anorexia nervosa, bulimia nervosa and controls during the stop-signal anticipation task. Two-sample t-tests of A) the parametric effect of stop-signal probability versus the implicit baseline (i.e., Go_{0\%} trials), B) the parametric effect of reaction time versus the implicit baseline, C) successful stop-signal versus the implicit baseline and D) successful stop-signal versus failed stop-signal activation for AN-BP, BN and control groups. Panels A & B represent proactive inhibition contrasts, whereas C & D relate to reactive inhibition. Maps represent significant clusters (voxel-wise p-value < .001, FWE cluster probability p-value < .05) and are presented in neurological orientation (L=left). See Figures 3-1 to 3-4 for details on cluster size, coordinates and associated test statistics.
Figure 4. Impaired proactive inhibition in bulimia nervosa is associated with increased superior frontal gyrus activity. A) Reaction time increased as a function of stop-signal probability in all groups; however, a significant group-by-probability interaction showed that women with BN did not slow to the same degree as controls in response to increasing stop-signal probability (p=.003). This impairment in proactive inhibition was associated with greater activity in B) the left superior frontal gyrus (k = 25 voxels, Z = 4.58, MNIx,y,z = -23, 33, 54, cluster defining threshold = p<.001, FWE-corrected cluster probability = p<.05) in BN relative to controls. C) A three-way interaction was related to stress-induced increases in the right superior frontal gyrus in BN relative to AN-BP (k = 34 voxels, Z = 4.52, MNIx,y,z = 22, 54, 36, cluster defining threshold = p<.001, FWE-corrected cluster probability = p<.05). The size, coordinates and test statistics of significant clusters from the whole-brain linear mixed-effects analysis of proactive inhibition are reported in Figure 4-1. Results are displayed in neurological orientation (L=left). Individual values are overlaid on the mean modulated % signal change by group. Error bars = SEM.
Figure 5. Stress reduces right ventromedial prefrontal cortex activity in anorexia nervosa (binge/purge subtype) during reactive inhibition. A) A significant three-way interaction indicated that right vmPFC activity was significantly reduced following acute stress compared to the neutral condition in AN-BP relative to controls (k = 32 voxels, Z = -4.19, MNI_X,Y,Z = 4, 45, -9, cluster defining threshold = p < .001, FWE corrected cluster probability = p < .05). The size, coordinates and test statistics of significant clusters from the whole-brain linear mixed-effects analysis of reactive inhibition are reported in Figure 5-1. B) Change in average percent signal change for the vmPFC cluster from pre- to post-induction across conditions. Individual values are overlaid on the mean change in percent signal change (post – pre) by group.
Figure 6. Associations between prefrontal responses during inhibition and ad libitum consumption. A) Greater vmPFC responses during reactive inhibition (Successful Stop vs. Failed Stop) were negatively related to food consumption during the free choice meal. See Figure 6-1 for the contents of the meal and corresponding macronutrient information. B) Increased left superior frontal gyrus responses to greater stop-signal probability were positively associated with food intake. Observations within the same subject are modelled with a line of best fit that reflects the overall brain-behavior association. While effects were derived from linear mixed-effects models, repeated measures correlations were computed for visualization, using the rmcorr R package (Bakdash & Marusich, 2017).
