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Motivational and neural correlates of self-control of eating: A combined neuroimaging and experience sampling study in dieting female college students

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ABSTRACT

Self-regulation is a critical ability for maintaining a wide range of health behaviors, especially in preventing overeating and weight gain. Previous work has identified various threats to self-control in the eating domain, chief among which are desire strength and negative affect. In the present study, we examined individual differences in college-aged dieters' experiences of these threats as they encountered temptations to eat in their daily lives, and tested whether these differences characterized sub-groups of dieters with divergent self-control outcomes. Specifically, 75 dieting females (age range: 18–23) participated in a combined functional magnetic resonance imaging (fMRI) and experience sampling study. Participants passively viewed food cues during a fMRI session, and then reported their daily eating behaviors for one week via ecological momentary assessment. We examined the characteristics of dieters who exhibited the most favorable combination of the aforementioned factors (i.e., low desire strength and positive mood) and who were thus most successful at regulating their eating. These dieters endorsed more autonomous reasons for their self-regulatory goals, and during the food cue reactivity task more readily recruited the inferior frontal gyrus, a brain region associated with inhibitory control. We suggest that these motivational and neural correlates may also be implicated in self-regulation of other important health behaviors.

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Self-regulation is a critical human capacity that ensures survival of the individual, as well as that of groups and our species as a whole (Heatherton, 2011), but failures abound. The current obesity epidemic and the accompanying rise of the dieting industry suggests that failures to exert self-control in the eating domain are especially prevalent (Norcross, Mrykalo, & Blagys, 2002). Importantly, failure to achieve long-term goals can arise from a series of small, seemingly innocuous decisions—a second serving of cake at the party, indulging in ice cream on a hot day, or stopping at the candy aisle in the supermarket. In the present study, we focused on self-regulation challenges in the dieting population, a group that is prone to lapses in self-control (Herman & Polivy, 1980). Moreover, we chose to study college-aged females because early adulthood is a unique time in which individuals no longer have external constraints (e.g., parental monitoring) on behavior, especially health and eating behaviors (see Nelson, Story, Larson, Neumark-Sztainer, & Lytle, 2008 for a review). Characterizing self-control outcomes in this population could therefore advance our understanding of how and when self-control is successfully exerted, as well as when it might break down and result in failure.

Previous research has identified multiple factors that increase the likelihood of self-control failure, but two that are especially problematic are desire strength and negative affect (Heatherton & Wagner, 2011; Wagner & Heatherton, 2015). Desire is a conscious feeling or state of "wanting" something (Kavanagh, Andrade, & May, 2005). It originates in automatic affective and cognitive responses to rewarding stimuli, which can be either external (e.g., smell of warm apple pie) or internal (e.g., thinking about a chocolate bar). If not resisted, desire drives behaviors aimed at indulging the desire, especially if these behaviors are easy to accomplish (Hofmann & Van Dillen, 2012). Conversely, resisting desires requires self-control; this occurs to the extent that a given desire

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stands in conflict with higher-order goals, such as dieting or health goals (e.g., Hofmann, Baumeister, Förster, & Vohs, 2012; Kotabe & Hofmann, 2015). Since every experience of desire represents a risk of acting on that desire, it stands that frequent and strong desires are more likely to be enacted, thus posing a greater threat to successful self-regulation. This was recently shown by Hofmann and colleagues, who found that desire strength predicted the rates of enactment, especially when these desires were resisted. That is, people were much less likely to successfully resist a strong desire than a weak desire (Hofmann et al., 2012). So, for dieters, experiencing weaker desire should result in more effective self-regulation, including better overall diet adherence.

An additional threat to self-regulation is negative affect (see Wagner & Heatherton, 2015 for a review). Indeed, being in a bad mood has been linked with self-regulation failures involving decision-making (Leith & Baumeister, 1996), gambling (Raghunathan & Pham, 1999), alcohol consumption (Witkiewitz & Villarroel, 2009), and binge eating (Heatherton & Baumeister, 1991). Conversely, positive affect is beneficial when self-regulatory resources have been compromised (Tice, Baumeister, Shmueli, & Muraven, 2007) and has been associated with behaviors that promote health and well-being (e.g., Sirois, Kitner, & Hirsch, 2015).

Although many studies have examined the effects of desire strength and affect separately, few studies have examined them together. Additionally, it is unclear whether college-aged dieters might differentially experience joint effects of these factors in their daily lives. Specifically, if these factors are experienced in a roughly two-by-two, orthogonal fashion (i.e., weak or strong desire, coupled with negative or positive mood), there are two possibilities for how they can combine to influence self-regulation: self-regulation is disrupted when *either* strong desire or negative mood is present (such that, by implication, the combination of weak desire with positive mood results in better self-regulation than the other three groupings), or when *both* are experienced (such that the combination of strong desires with negative mood results in worse self-regulation than the other three groupings). In the present study, we tested these possibilities by examining which combination is most beneficial for/detrimental to effective self-regulation of eating behavior. We also examined specific motivational and neural markers that may underlie dieters' success in regulating their eating.

One potential marker of successful regulatory processes may be motivation, an integral part of both goal setting and goal pursuit. Importantly, motivation differs not only in degree (i.e., how much motivation a person has) but also in the reasons why the goal is selected and pursued in the first place. Indeed, self-determination theory (Deci & Ryan, 2000) distinguishes between engaging in a behavior because of inherent interest and/or personal importance (termed autonomous motivation), and engaging in the behavior to please others or because of feelings of shame or obligation (controlled motivation). Research has shown that autonomous motivation in particular is advantageous for a variety of health behaviors, including healthy eating behaviors (Pelletier, Dion, Slovinec-D'Angelo, & Reid, 2004), smoking cessation (Williams, Gagné, Ryan, & Deci, 2002), self-care of diabetes (Senécal, Nouwen, & White, 2000), and exercise (Edmunds, Ntoumanis, & Duda, 2006). Recently, Milyavskaya and colleagues have suggested that these beneficial effects of autonomous motivation occur because of decreased impulsive attraction towards goal thwarting temptations, such as highly palatable foods (Milyavskaya, Inzlicht, Hope, & Koestner, 2015). Based on these consistent findings, we expected that dieters in our sample who express autonomous—but not controlled—motivation to restrict their food intake would experience the more beneficial combination of desire strength and mood. That is, we predicted those dieters who more frequently experience weak desires and positive mood to generally be more autonomously motivated, while those who frequently experience strong desires and negative moods to be relatively less autonomously motivated to control their eating behavior.

Given that autonomous motivation is generally associated with better goal adherence and favorable self-control outcomes, we considered potential neural correlates of self-regulatory capacity, which would help establish a potential brain-behavior relationship in the college-aged dieting population. Neuroscientists and psychologists alike have utilized functional brain imaging to identify brain regions and systems believed to underlie multiple behaviors of interest. Some of the initial human neuroimaging studies drew from animal models and focused on appetitive behaviors, including the experience of pleasure and reward (Berridge & Kringelbach, 2008). Over the years, many research groups have utilized brain imaging to delineate brain-behavior relationships underlying appetite and eating (for a review, see Carnell et al., 2012). For example, blood oxygen level dependent (BOLD) activity in the ventral striatum is predictive of college-aged students giving in to daily temptations to eat (Lopez, Hofmann, Wagner, Kelley, & Heatherton, 2014) and long term weight gain (Demos, Heatherton, & Kelley, 2012). However, participants in these studies came from the non-dieting population, comprised of individuals who generally are not motivated to control their eating. So, for the purposes of the present study in which we only recruited dieters, we wanted to hone in on a neural correlate of self-control. One brain region that has been consistently associated with successful control of impulses during inhibitory control tasks is the ventrolateral prefrontal cortex, namely the inferior frontal gyrus (IFG) (Aron, Robbins, & Poldrack, 2004; Hampshire, Chamberlain, Monti, Duncan, & Owen, 2010). When faced with tempting food cues, some dieters spontaneously show increased BOLD activity in executive control regions (e.g., the IFG), which may reflect inhibitory processes (i.e., stopping an automatic prepotent response). Such signals may index dieters' capacity to exert control over impulses to eat. Recently, IFG activity during inhibitory control tasks has been associated with successful regulation of real world cigarette craving (Berkman, Falk, & Lieberman, 2011) and food desires (Lopez et al., 2014). Here, we measured IFG activity as dieters completed a food cue reactivity task and then linked this activity to levels of reported desire strength and mood in their daily lives.

In sum, the present study examined the relationship between college-aged dieters' daily experiences of desire and mood and their self-control, with a focus on motivational and neural correlates of differences observed in these self-regulatory processes. In order to examine mood and desire as they unfold in real time, we conducted an experience sampling study with chronic dieters. Unlike laboratory or self-report methods that are frequently criticized for their lack of ecological validity and reliance on retrospective memory, experience sampling provides a more proximal and accurate method of assessing people's thoughts, emotions, and behaviors in the course of their day-to-day lives—at the time that the experience takes place (Csikszentmihalyi & Larson, 1987; Shiffman, Stone, & Hufford, 2008).

Given the exploratory and novel nature of this study, we had two competing hypotheses regarding the possible combinations of mood and desire in chronic dieters: 1) negative mood with high desires is related to particularly unsuccessful self-regulation (compared to the other 3 combinations); 2) positive mood with low desire is related to especially successful self-regulation (compared to the other 3 combinations). We also examined whether individual differences in autonomous motivation and IFG activity were linked to experiencing favorable or unfavorable combinations of these factors. That is, are some experiences (e.g.

weak desire with positive mood, or strong desire with negative mood) particularly good (bad) for in-the-moment self-regulation? And do people who generally have more of these positive or negative experiences differ in motivation and IFG activity?

1. Method

Seventy-five female participants were recruited for a study that consisted of a functional magnetic resonance imaging (fMRI) session followed by a 1-week sampling of daily behaviors using experience sampling. During the fMRI session, participants first underwent a procedure that induced a cognitive state associated with self-control failure, namely self-regulatory depletion—a significant threat to self-control among dieters that often leads to disinhibited eating (e.g., Vohs & Heatherton, 2000). We employed this procedure because we wanted to create a situation that would most closely resemble typical "risk" situations of self-regulatory failure, so as to increase the correspondence between the type of psychological situation experienced in the lab and critical situations faced by dieters in daily life. After this manipulation, they completed a validated cue reactivity task in which they viewed appetizing food images that have been shown previously to robustly elicit reward activity (Wagner, Boswell, Kelley, & Heatherton, 2012; see Fig. 1 for a depiction of the trial structure). Following the scanning session, in order to examine participants' food desires and mood levels as they unfold in real time, we employed an experience sampling protocol adapted from previous work (Hofmann et al., 2012). Participants were prompted several times a day to report their eating behaviors on mobile surveys delivered by the SurveySignal survey management platform (Hofmann & Patel, 2015). Specifically, participants indicated the frequency and strength of the food desires they experienced and how often they gave in to those desires and ate. They also reported the level of positive/negative mood at desire onset.

1.1. Participants

We recruited 75 females from the Dartmouth College community (mean age = 19.38, range = 18–23[1]). During the recruitment phase, participants were pre-screened with the Revised Restraint Scale (Heatherton, Peter, Polivy, King, & McGree, 1988; Herman & Polivy, 1980) to verify chronic dieting tendencies; each participant had to report a composite score of 16 or greater (across both "Concern for Dieting" and "Weight Fluctuation" subscales) to be eligible to participate in the study (see Heatherton, Polivy, & Herman, 1991). Participants were also right-handed, had normal or corrected-to-normal vision, and reported no psychiatric or neurological disorders. We ran only female participants to ensure consistent effects from previous studies of food cue reactivity (e.g., Demos et al., 2012), and accordingly we sampled from the same population. Participants were run at multiple times of day (AM and PM), and given potential time-of-day effects on neurophysiological activity, we controlled for this in all models with brain activity as the outcome measure. All participants' body mass index (BMI) and body fat percentage were measured using a Tanita TBF-300A Body Composition Analyzer (Tanita Corporation, Arlington Hights, IL). Study participants gave consent in accordance with Dartmouth's Committee for the Protection of Human Subjects, and were debriefed following both fMRI and experience sampling components of the study.

[1] Given the possibility of age-related effects, age was controlled for in all reported models.

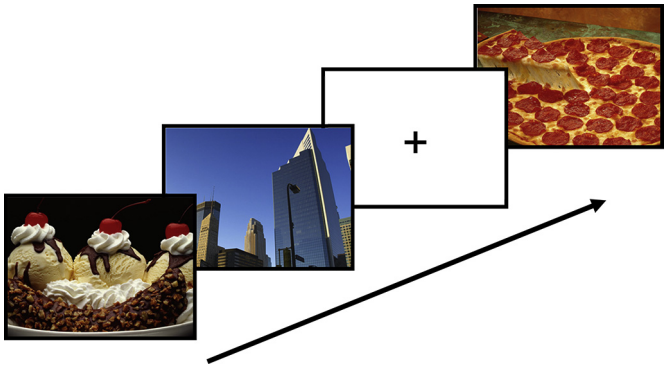

Fig. 1. Depiction of cue reactivity task, in which food images were interleaved with control stimuli (nature scenes) as participants made simple indoor/outdoor judgments. Each image was displayed for 2 s, with jittered intervals of fixation (baseline).

1.2. Brain imaging procedure and analysis

fMRI data were collected with a 3-T Philips Intera Achieva scanner (Philips Medical Systems, Bothell, WA) equipped with a SENSEitivity Encoding head coil. Stimuli were presented using SuperLab 4.0 (Cedrus Corporation) and projected to an Epson ELP-7000 LCD screen positioned at the end of the magnet bore. Participants were able to view the screen via a mirror mounted on the head coil. While in the scanner, they completed a cue reactivity task in which they viewed a set of images and were instructed to make perceptual judgments as to whether each image depicted an indoor or outdoor scene. All judgments were made with a corresponding button press on a Lumina LU-400 fMRI response pad. Since the task incorporated different image types other than food, including images of people and nature scenes, participants were unaware of our intention to only inspect food cue specific activity. The cue reactivity task employed a rapid, event-related design, with all design parameters and trial timing following those from previous studies that administered the task (e.g., Lopez et al., 2014).

All fMRI data were preprocessed and analyzed using Statistical Parametric Mapping software (SPM8, Wellcome Department of Cognitive Neurology, London, UK) in conjunction with a suite of tools for automating and batching (freely available at https://github.com/ddwagner/SPM8w). For each functional (EPI) run, data were corrected for differences in slice-timing and preprocessed to remove sources of artifact and noise. Functional data were realigned within and across runs to correct for head movement and were unwarped to reduce any residual movement-related image distortions. Functional data were based on the SPM8 EPI template that follows the ICBM 152 brain atlas (Montreal Neurological Institute). To spatially smooth the normalized images, a Gaussian kernel was applied (6-mm full width at half maximum). Six subjects' data were excluded from further analysis, due to excessive motion-related artifact (resulting N = 69).

For every subject, we ran a general linear model (GLM) that included task conditions and covariates of non-interest (e.g., six motion parameters from realignment correction, a linear trend to account for drifts in scanner signal). All subjects' GLMs were convolved with the canonical hemodynamic response function in SPM and used to estimate voxel-wise parameter estimates for the contrast of food cue related activity versus activity related to control images (i.e., nature scenes) used in all subsequent analyses. Whole-brain contrast images for each subject were generated and submitted to a second-level analysis (allowing for subject to be treated as a random effect), forming a group T-map representing food cue specific activity across the brain. To avoid bias in selection

of brain regions-of-interest (ROI) associated with inhibitory control, we placed a 6-mm spherical mask centered on coordinates in the left IFG from a previous study that implicated this region in successful self-control of food desires (coordinates in MNI space: -36, 30, -3; see Lopez et al., 2014).

1.3. Motivation for dieting

The Regulation of Eating Behavior Scale (REBS; Pelletier et al., 2004) was used to assess participant's motivation for restricting their food intake. The scale consists of 24 items assessing six types of motivation ranging from intrinsic to amotivated. These were used to create two separate scales of *autonomous* motivation (combining intrinsic, integrated and identified regulation, e.g., "Eating healthy is part of the way I have chosen to live my life.") and *controlled* motivation (combining introjected and extrinsic regulation; e.g., "I feel I must absolutely be thin"). All items were rated on a 1 (*strongly disagree*) to 7 (*strongly agree*) scale. Both subscales were reliable: $\alpha = 0.90$ for *autonomous* motivation and $\alpha = 0.82$ for *controlled* motivation. There was a small correlation between the subscales, $r(66) = 0.233$, $p = .06$.

1.4. Experience sampling procedure

The experience sampling protocol followed that of previous studies with similar designs (e.g., Hofmann et al., 2012). Participants were randomly prompted seven times a day between waking hours (9 a.m.–11 p.m.) on their smartphone. On every occasion, they reported on their momentary food desires. Specifically, they were first asked whether they were experiencing a current or recent (within the past 20 min) desire for food. If they answered "yes," they then indicated: (1) desire strength: the experienced strength of the food desire on a scale from 0 (*none at all*) to 6 (*irresistible*); (2) mood: how positively or negatively they felt at the onset of the desire from −3 (very bad) to 3 (very good); and (3) enactment: whether or not they gave in to the desire and already ate (*yes*/*no*). Participants also reported their hunger level on a scale from 0 (*not at all hungry*) to 6 (*very hungry*). Mean values for all assessed variables were calculated for each subject and aggregated across all complete observations for that subject in the sampling period ($M_{observations} = 31.36$; SD = 8.59; range = 8–44).

Because this sample solely consisted of chronic dieters, overall reported frequency of food desires was relatively low (mean for all subjects = 35.3%), but there was marked variability across subjects (SD = 15.7%, range = 5.4%–71%). These figures for each subject represent the number of instances during the sampling period in which they reported a current or recent food desire, divided by the total number of complete observations for that subject. Only those instances where a desire was reported are used in the present analyses (714 total observations). We also calculated the proportion of desires that resulted in self-regulation failure (i.e., where the participant enacted each desire) by dividing the number of enacted desires by the total number of desire episodes (e.g., if someone gave in and ate the desired food 4 times out of twenty, her enactment rate would be 20%).

2. Results

2.1. Determining most beneficial combination of mood and desire strength

To test our two contrasting hypotheses, we first tested for additive effects of desire strength and mood by running a k-medoid clustering algorithm. We submitted the sample to a k-medoid clustering algorithm based on normalised scores of desire strength and mood. Any cases of | *Z*-score | ≥ 3 on either factor were removed to reduce the influence of extreme outliers (1 outlier removed, final N = 68). Importantly, desire strength and mood were not correlated with one another, $r(67) = -0.18$, $p = .14$. This data-driven approach allowed us to identify distinct sub-groups in the sample that might exhibit different combinations of these factors and subsequently perform group analyses to test hypotheses of interest. In order to determine the appropriate number of (k) clusters, we iteratively ran the algorithm starting at k = 2 clusters, used the stopping criterion of maximal mean silhouette width, an established metric for cluster stability (see Rousseeuw, 1987). The algorithm returned 4 stable clusters (Mean silhouette width across clusters = .458, range = .313–.530), with cluster sizes of 23, 11, 13, and 21, respectively. The clusters roughly followed the hypothesized pattern (described above) of four combinations of desire strength and mood in a 2-by-2 fashion (weak/strong desire by negative/positive mood; see Fig. 1). Thus, as expected, each subject could be characterized by a specific combination of desire strength and mood, as indicated by their discrete cluster or group assignment. Eleven participants (Group 2) could be characterized as experiencing weak desires and positive mood, representative of the most favorable combination of the two factors, while 13 participants experienced strong desires along with a negative mood (Group 3). Preliminary analyses showed that groups did not differ from one another on BMI ($F(3, 64) = 0.481$ $p = .697$) or scores on the Restraint Scale ($F(3, 64) = 0.433$ $p = .730$).

To investigate which of these specific combinations of desire and mood were representative of effective self-regulation, we performed a one-way analyses of variance (ANOVA) with assigned cluster as the grouping variable and enactment rate as the dependent variable, followed by contrasts to compare 1) the group with low desire and positive mood to other groups; 2) the group with high desire and negative mood to other groups (see Fig. 2). Although the omnibus effect was not significant ($F(3, 64) = 1.764$ $p = .163$), planned contrasts comparing the low-desire, positive-mood group (Group 2) and the higher-desire, negative-mood group (Group 3) found a significant difference in enactment, $b = -0.192$, $t(64) = -2.123$, $p = .038$, such that Group 2 only gave in to desires to eat 35.5% of the time, whereas Group 3 enacted 54.7% desires (see Fig. 3). Furthermore, to examine whether the group with most beneficial combination of desire and mood fared better than any group experiencing a threat (or combination of threats) to self-control, we compared Group 2 to all other groups, all of which

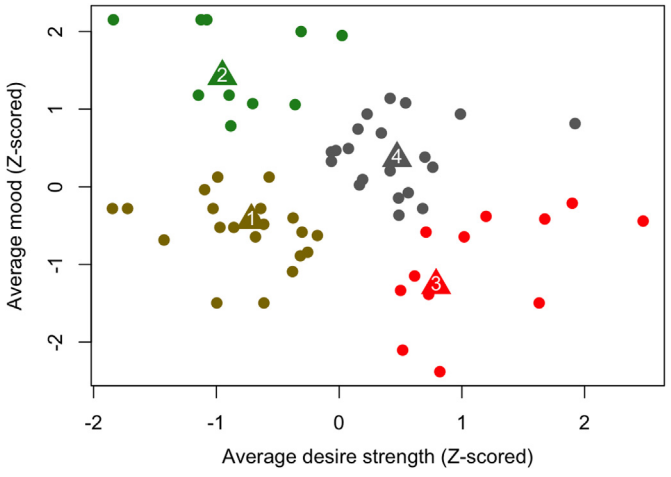

Fig. 2. Bi-variate plot depicting k-medoid cluster assignments based on average desire strength and mood.

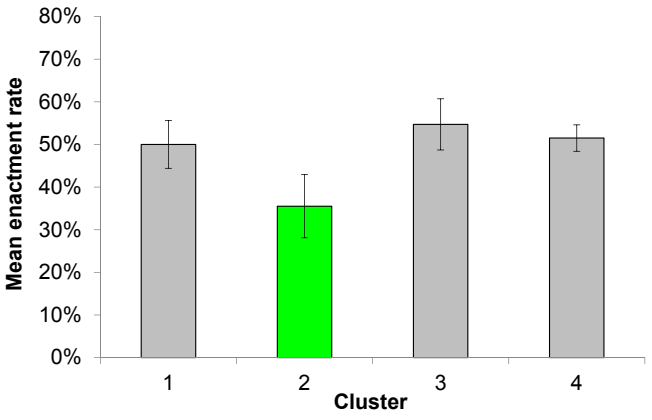

Fig. 3. Mean enactment rate by cluster, with the sub-group showing most beneficial combination of mood and desire strength (i.e., positive mood and low desire) highlighted in green (error bars represent standard error of the mean). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

had at least one threat working against them (i.e., higher desire, negative mood, or both). Compared to the other groups, Group 2 gave in less frequently to their desires for food, ($b = -0.166$, $t(64) = -2.264$, $p = .027$).

To rule out alternative (interactive) combinations of mood and desire strength, we also tested for interactive effects of mood and desire on enactment, both on the person level (i.e., the overall proportion of desires that each participant gave in to) and observation level (i.e., whether the participant gave in to a desire in the moment). On the person level, we ran a linear model in which we regressed desire strength, mood, and their interaction on mean enactment (while controlling for hunger). There was a trending effect of desire on enactment, $F(1,70) = 3.373$, $p = .071$, but there was no effect of mood, $F(1,70) = 2.380$, $p = .127$, and no interaction effect, $F(1,70) = 2.527$, $p = .116$. On the observation level, we used logistic multilevel regression in the Hierarchical Linear Modeling (HLM) software suite (Raudenbush, 2004), with momentary enactment as the dependent variable, and desire, mood, and their interaction as level-one predictors. We also included hunger as a level 1 covariate. All Level 1 predictors were group (person) mean-centered (see Table 1 for descriptive statistics of variables included in all multilevel regressions). No predictors in this model were significant except for hunger, $B_{log} = -1.00$, $p < .001$ (See Table 2 for all model results).[2]

Table 1
Descriptive statistics for all Level 1 and Level 2 variables and outcome measures used in multilevel models.

Level-1 predictors	*N*	*M*	*SD*	Min	Max
Desire strength	711	4.03	1.15	1	6
Mood	681	0.23	1.25	−3	3
Hunger	702	2.77	1.95	0	6
Level-2 Predictors	***N***	***M***	***SD***	**Min**	**Max**
Autonomous motivation	69	5.16	0.96	3	6.92
Controlled motivation	69	3.95	1.06	1.88	6.25
IFG activity	69	0.18	0.54	−1.05	1.68
Outcome measures					
Enactment	***N***	**%**			
No	349	49.5			
Yes	356	50.5			
Total	705				
Low desire/positive mood	***N***	**%**			
No	608	82.4			
Yes	70	9.5			
Total	678				

Table 2
Multilevel logistic regression of enactment on desire strength, mood, their interaction, and Level 2 predictors (controlling for hunger at Level 1 and controlled motivation at Level 2). Level 2 (person) predictors include autonomous motivation and IFG activity. (B_{log} = log odds; *OR* (*CI*) = odds ratio with confidence interval = *SE*: robust standard error).

Predictor	B_{log}	*OR* (*CI*)	*SE*	*p*
Base predictors (Level 1)				
Intercept	0.07	1.07 (0.82, 1.40)	0.13	.606
Desire strength	0.11	1.12 (0.59, 2.13)	0.33	.731
Mood	−0.25	0.78 (0.42, 1.42)	0.31	.408
Desire × Mood interaction	0.10	1.10 (0.95, 1.27)	0.07	.195
Hunger	−1.00	0.37 (0.31, 0.44)	0.09	<.001
Trait/brain predictors (Level 2)				
Autonomous motivation	<0.01	1.00 (0.77, 1.29)	0.13	.991
IFG	−0.05	0.96 (0.57, 1.61)	0.26	.860
Controlled motivation	−0.06	0.94 (0.73, 1.22)	0.13	.658

2.2. Correlates of most beneficial combination of mood and desire strength

Next, we examined whether there were differences in motivation among groups. Because only autonomous, but not controlled motivation was expected to be related to experiencing the favorable combination of desire and mood evident in Group 2, we ran two separate ANCOVAs examining the differences among groups on both types of motivation, each including the other motivation as a covariate. As expected, there were trending differences among groups on autonomous motivation ($F(3, 63) = 2.436$, $p = .073$), but not on controlled motivation ($F(3, 63) = 0.207$, $p = .891$). Follow-up contrasts showed that dieters with a favorable combination of desire and mood (Group 2) were more autonomously motivated than all other dieters combined ($b = 0.719$, $t(64) = 2.294$, $p = .025$; see Fig. 4). For our final analyses at the subject level, we tested for differences in spontaneous IFG activity, and found that there were differences among groups, $F(3, 63) = 4.955$, $p = .004$ (see Fig. 5). Follow-up contrasts again showed that those dieters with the beneficial desire/mood combination spontaneously recruited the IFG to a greater extent during the cue reactivity task ($b = 0.475$, $t(63) = 2.792$, $p = .007$).[3]

In addition to subject-level analysis via the clustering algorithm described above, we ran a multilevel regression model with the Hierarchical Linear Modeling (HLM) software suite (Raudenbush, 2004) to more closely inspect the associations among autonomous motivation, IFG activity, and momentary experiences of desire strength and mood. The model's dependent variable was dichotomous and represented favorable desire/mood episodes. We dummy coded it following logical conjunction, such that those observations in which participants reported moderate to weak desire strength (i.e., ≤3 on the 0–6 scale, described above) *and* positive mood (i.e., >0 on the −3 to 3 scale, also described above) were positively coded with a 1, while all other observations were coded with a 0. This variable was subjected to a logistic multilevel regression by specifying a Bernoulli model in HLM (Raudenbush,

[2] Importantly, desire frequency was not significantly predictive of likelihood of enactment, and it was not significantly associated with mean enactment rate.

[3] Although other brain regions were activated in the cue reactivity task above a statistical threshold, we focused solely on the IFG as an *a priori* region-of-interest based on its robust activations in previous studies of inhibitory control. This was done in order to safeguard against some statistical pitfalls that come with doing a whole brain analysis (see Poldrack, 2007).

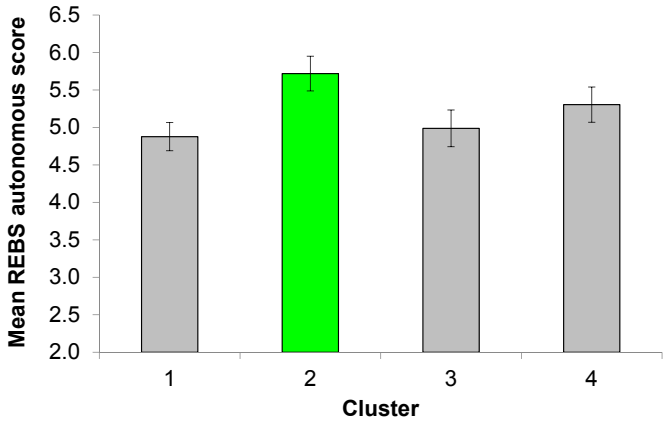

Fig. 4. Mean REBS autonomous motivation scores by cluster/group, with the sub-group showing most beneficial combination of mood and desire strength highlighted in green (error bars represent standard error of the mean). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

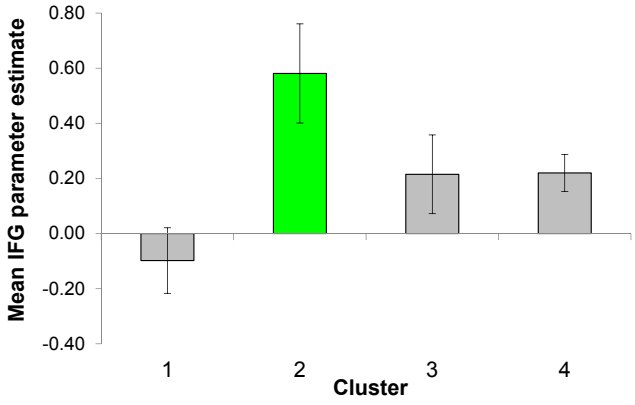

Fig. 5. Mean IFG activity (food versus control contrast) by cluster/group. The sub-group showing most beneficial combination of mood and desire strength highlighted in green (error bars represent standard error of the mean). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2004). Our key predictors were at Level 2: subjects' autonomous motivation scores and their parameter estimates of IFG activity (from the food versus other image contrast) during the food cue reactivity task. Importantly, since we wanted to account for participants' varying levels of reported hunger while testing for the main effects of interest, we included hunger at Level 1 as a covariate. All Level 1 predictors were person-mean centered, and Level 2 predictors were grand-mean centered (see Enders & Tofighi, 2007 for centering recommendations). In line with recommendations recently set out by Barr, Levy, Scheepers, and Tily (2013) for linear mixed-effects models, we specified a "maximal model" by including both random intercept and random slope terms (Barr et al., 2013). Supporting person-level analyses, autonomous motivation predicted a greater likelihood of favorable desire/mood episodes, $b_{log} = 0.387$, $OR = 1.47$, 95% CI [1.05; 2.07], $p = .027$, such that each point increase in autonomous motivation was associated with a 50% greater likelihood of experiencing a favorable (compared to a less favorable) desire. Similarly, IFG activity was also related to a greater likelihood of a low desire/positive mood episode, $b_{log} = 0.836$, $OR = 2.31$, 95% CI [1.44; 3.70], $p = .001$. As before, controlled motivation was not a significant predictor, $b_{log} = -0.097$, $OR = 0.91$, 95% CI [0.71; 1.16], $p = .427$.

3. Discussion

In this study we examined the roles of desire strength and mood in how dieters regulate their eating behaviors, as well as motivational and neural correlates that support successful regulation. We tested for joint (additive) effects of desire strength and mood on enactment of food desires by running a k-medoid clustering algorithm. This algorithm identified a sub-group of dieters who experienced, on average, a particularly beneficial combination of these factors—exemplified by low desire and positive mood—that supported successful self-regulation. Indeed, these dieters were least likely to succumb to their desires, and were thus more successful in their self-regulatory efforts. This finding implies that in real world experiences of temptations to eat, decreased desire strength and positive mood come together and serve as a buffer to prevent dieters from succumbing to those temptations to eat, presumably less often than they might otherwise. Additionally, given our *a priori* interest in autonomous motivation and brain activity in ventrolateral prefrontal cortex (i.e., the IFG) representing trait level markers of greater self-control capacity, we tested for group effects using these two variables. Both autonomous motivation and IFG activity characterized the most successful sub-group of dieters in our sample, and also predicted greater likelihood of experiencing the favorable combination of positive mood with weak desires at any given moment.

This study builds on previous research that suggests that self-control can be built by establishing good habits, removing potential sources for desire, and generally setting up your environment in such a way that the availability and opportunity of temptations is reduced (e.g., Fujita, 2011). Our results suggest that part of such effective self-regulation includes down-regulating desires and up-regulating mood. Other research has found that activating a goal leads to more negative implicit evaluations of tempting stimuli and more positive evaluations of stimuli related to the goal itself (Fishbach, Zhang, & Trope, 2010). Although all the participants in the current study were chronic dieters, and so likely had dieting goals active much of the time, perhaps there were some differences among them. For example, it may have been the case that only the chronic dieters who were autonomously motivated had the dieting goal consistently activated, since its relation to values, interests and other goals might make the dieting goal more accessible (see Milyavskaya et al., 2015, for similar arguments).

In this study, we focused on desire strength and mood as factors that impact self-regulation of eating, especially the combination of down-regulation of desire and experiences of positive mood. However, many other processes are likely at play. For example, distraction from a temptation has been shown to aid self-regulation (Mischel & Ebbesen, 1970). Similarly, attentional bias, or the extent to which cues in the environment automatically capture a person's attention, has also been shown to affect self-regulation (see Sheeran, Gollwitzer, & Bargh, 2013 for a review). Future research is needed to better understand how these processes, in addition to desire strength and mood, differentially act in combination to influence the course of self-regulatory outcomes.

Looking at individual differences, we found that participants with the most successful outcomes were those pursuing their dieting goals for autonomous reasons. This is in line with multiple studies that have repeatedly shown that autonomous motivation is beneficial for health outcomes and successful goal pursuit (Deci & Ryan, 2000). Along with other recent studies suggesting that autonomous motivation affects the impulsive aspect of self-regulation (Milyavskaya et al., 2015; Werner, Milyavskaya, Foxen-Craft & Koestner, 2016), our findings suggest that the reason for these benefits is that autonomous motivation decreases problematic desires (rather than increasing effortful self-control). This also