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Suppressing images of desire: Neural correlates of chocolate-related thoughts in high and low trait chocolate cravers

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ABSTRACT

Chocolate is the most often craved food in Western societies and many individuals try to resist its temptation due to weight concerns. Suppressing chocolate-related thoughts might, however, lead to paradoxical enhancements of these thoughts and this effect might be more pronounced in individuals with frequent chocolate cravings. In the current study, neural and cognitive correlates of chocolate thought suppression were investigated as a function of trait chocolate craving. Specifically, 20 high and 20 low trait chocolate cravers followed suppression vs. free thinking instructions after being exposed to chocolate and neutral images. Enhanced cue reactivity was evident in high trait chocolate cravers in that they reported more chocolate-related thoughts selectively after chocolate images compared to their low trait craving counterparts. This cue reactivity was mirrored neurally by higher activation in the ventral and dorsal striatum, demonstrating enhanced reward system activity. Unexpectedly, high trait chocolate cravers successfully reduced their elevated chocolate thoughts in the suppression condition. This lends support for the use of thought suppression as a means of regulating unwanted thoughts, cravings and imagery. Whether this thought manipulation is able to curb the elevated cue reactivity and the underlying reward sensitivity in chocolate cravers in applied settings remains to be shown.

1. INTRODUCTION

Food craving refers to an intense desire to consume specific foods, of which chocolate is the most often craved one in Western societies (Richard, Meule, Reichenberger, & Blechert, 2017b; Rozin, Levine, & Stoess, 1991; Weingarten & Elston, 1991). Chocolate craving is a multidimensional construct as it includes cognitive (e.g., thinking about chocolate), emotional (e.g., desire to eat, changes in mood), behavioral (e.g., seeking and consuming chocolate), and physiological (e.g., salivation) aspects (Cepeda-Benito, Gleaves, Williams, & Erath, 2001; Rodriguez-Martin & Meule, 2015). Individuals differ with respect to the frequency and intensity of chocolate cravings, with some experiencing frequent and intense chocolate cravings (high trait chocolate cravers) while others rarely doing so (low trait chocolate cravers). High trait chocolate craving has been associated with a higher implicit preference for chocolate and more frequent chocolate consumption, but also with more feelings of guilt resulting from eating chocolate (Benton, Greenfield, & Morgan, 1998; Cartwright & Stritzke, 2008; Meule & Hormes, 2015; Richard, Meule, Friese, & Blechert, 2017a).

Food thought suppression

Thought suppression refers to the intentional avoidance of certain thoughts and can be thought of as a way of avoiding cravings. Cognitive-behaviorally oriented treatments of binge eating typically feature strategies of thought control (e.g., reappraisal and distraction; Munsch, et al., 2007). However, it has also been shown that suppressing thoughts can paradoxically result in thinking about the suppressed item more frequently (Abramowitz, Tolin, & Street, 2001; Wegner, 2009; Wegner, Schneider, Carter, & White, 1987). Similarly, correlational evidence indicates that more frequent food-related thought suppression is associated with higher trait chocolate craving (Van Gucht, Soetens, Raes, & Griffith, 2014). However, findings from experimental studies, which would allow a causal inference about the relationship between food thought suppression and the occurrence of thoughts about food or food craving, respectively, are mixed (Erskine & Georgiou, 2013). For example, while some studies found increased food-related thoughts under instructions to suppress these thoughts, the majority of studies found such effects only in a subgroup of individuals such as restrained or disinhibited eaters (O'Connell, Larkin, Mizes, & Fremouw, 2005; Oliver & Huon, 2001; Soetens & Braet, 2006; Soetens, Braet, Dejonckheere, & Roets, 2006). Other studies found that when participants were instructed to suppress their thoughts about a food, they showed higher *subsequent* consumption of that food (Erskine, 2008; Erskine & Georgiou, 2010; Hooper, Sandoz, Ashton, Clarke, & McHugh, 2012) or worked harder in a computer task to earn chocolate (Johnston, Bulik, & Anstiss, 1999). Thus, while these studies examined effects of food-related thought suppression on subsequent behavior, the cognitive effects (i.e., whether thought suppression actually increased the thoughts about food) were not assessed. To conclude, findings about the effects of food-related thought suppression are inconsistent and, to date, immediate effects of attempting to suppress thoughts about chocolate on the occurrence of chocolate-related thoughts and its relationship to trait chocolate craving have not been investigated yet. In addition, the neural correlates of such manipulations are largely unknown.

Neural correlates of food cue processing and chocolate craving

Cognitive processing of high-calorie *food cues* is accompanied by activation of reward-related brain regions such as the anterior cingulate cortex, orbitofrontal cortex, insula, amygdala, and striatum (Garcia-Garcia, et al., 2013). Moreover, several subgroups of individuals have been identified that show particularly high activation in these brain areas in response to palatable food cues. For example, adolescents who gained weight showed increases in striatal response to palatable food cues (Stice & Yokum, 2016) and, similarly, higher dorsal and ventral striatum activation in response to high-calorie food cues was found in obese versus normal-weight adults (Farr, Chiang-shan, & Mantzoros, 2016; Stoeckel, et al., 2008). Importantly, it has recently been reported that higher trait food craving scores were associated with higher activation in the ventral striatum in response to high- versus low-calorie food cues (Ulrich, Steigleder, & Grön, 2016).

A number of studies have looked into the neural processing of *chocolate cues* and effects of trait chocolate craving in particular, reporting neural structures similar to those described above (Asmaro & Liotti, 2014). For example, Rolls and McCabe (2007) demonstrated that the sight of chocolate went along with higher activation of the orbitofrontal cortex and ventral striatum in chocolate cravers relative to non-cravers. Similarly, a chocolate cue exposure with response prevention paradigm showed that activation in the striatum was linked to craving strength (Frankort, et al., 2014) and subsequent chocolate consumption (Frankort, et al., 2015).

Neural correlates of regulation of food craving

In recent years, a substantial amount of studies has been dedicated to the question whether and how activation of reward-related brain regions in response to high-calorie food cues can be modulated, e.g., by using cognitive craving regulation strategies (Giuliani, Mann, Tomiyama, & Berkman, 2014; Hollmann, et al., 2012; Scharmüller, Übel, Ebner, & Schienle, 2012; Yokum & Stice, 2013). Kober et al. (2010), for instance, instructed participants to reduce their craving with cognitive reappraisal strategies. They found that higher activity in the dorsolateral prefrontal cortex (dlPFC) was correlated with decreases in craving and, importantly, this relationship was mediated by reduced activation of the ventral striatum. In other studies, participants were instructed to use either thought suppression or reappraisal to reduce craving, both of which also modulated activation in similar regions (i.e., ventral striatum, among others; Siep, et al., 2012; Wang, et al., 2009). To conclude, increasing evidence suggest that palatable food cues activate reward-processing related brain regions such as the striatum and that these activations can be downregulated via cognitive strategies such as reappraisal or suppression. However, such a modulation has not been investigated particularly in response to chocolate-related cues and as a function of trait chocolate craving.

The present study

In the current study, high and low trait chocolate cravers' brain activations during a thought suppression task were investigated. Specifically, participants were presented with pictures of chocolate or neutral objects and were instructed to subsequently either suppress their thoughts about these stimuli or think freely. Based on the findings with trait food cravers in general (Ulrich, et al., 2016) and chocolate cravers in particular (Rolls & McCabe, 2007), it was expected that high trait chocolate cravers would show higher cue reactivity relative to low trait chocolate cravers in the context of chocolate trials, irrespective of instructions (*cue reactivity hypothesis*). On an experiential level, this should manifest in more positive valence and higher craving ratings for, as well as more reports of thoughts about, chocolate relative to neutral objects. Similarly, on a neural level this cue reactivity was expected to manifest in stronger activation in the ventral and/or dorsal striatum in response to chocolate versus neutral objects in high relative to low trait chocolate cravers. Regarding the suppression manipulation, previous research in restrained and disinhibited eaters indirectly suggests that high trait craving individuals might fail in successfully suppressing chocolate-related thoughts (*suppression failure hypothesis*), indicative of an inability to control – or disengage from – craved cues. This would manifest experientially in more frequent chocolate thought reporting and neurally in reduced control network recruitment (e.g. dlPFC; Kober, et al., 2010) only in high trait chocolate cravers during suppression of chocolate thoughts compared to free thinking.

2. METHODS

2.1 Participants

A total of 131 university students were recruited through student mailing lists, flyers shared on social media platforms and in psychology classes. All participants completed the chocolate version of the Food Cravings Questionnaire-Trait (FCQ-T-r; Meule & Hormes, 2015) online. The FCQ-T-r measures the frequency of chocolate craving experiences in general and consists of 15 items (e.g., "When I'm craving chocolate, thoughts of eating it consume me."), which are scored on a 6-point scale (1 [*never/not applicable*] to 6 [*always*]; Cronbach's $\alpha = .975$). Participants scoring in the upper (high trait chocolate cravers) and lower tertiles (low trait chocolate cravers) of the distribution ($n = 56$) were interviewed on the telephone for exclusion criteria (i.e., current dieting, medication, chocolate liking and consumption, and food allergies); of these, 54 participants met requirements and agreed to participate. The datasets from 14 participants had to be excluded because they did not comply with the laboratory tasks ($n = 7$) or showed excessive head movements ($n = 4$), and due to technical problems during fMRI-scanning ($n = 3$). Complete datasets were obtained from 40 individuals (mean age was 26.0 years, $SD = 6.33$, range 19-41): 20 high trait chocolate cravers (5 males) and 20 low trait chocolate cravers (5 males). Participants reported no current mental or neurological disorders, no current use of prescriptive medication except for oral contraceptives and no current alcohol or drug dependence. All participants read and signed an informed consent form that had been approved by the ethics committee of the University of Salzburg.

2.2 Procedure

At the beginning of the study, all participants completed self-report measures, including demographic questions and questionnaires assessing state and trait chocolate craving (Meule & Hormes, 2015), followed by instructions to perform the fMRI-task correctly. During the fMRI-task, they were repeatedly instructed to suppress thoughts about chocolate (or a neutral object) or to freely think of anything that came to their mind, while keeping their eyes open. The task consisted of four blocks, two for each stimulus type (chocolate and neutral objects; images retrieved from Blechert, Meule, Busch, & Ohla, 2014)[1]. Each block started with an instruction (6 s) displaying an image of the target item together with the two instructions that would subsequently be given: a green traffic light, to signal free thinking ("You can think of anything"), and a red traffic light, to signal suppression of any thoughts about the target item ("Do not think about chocolate/neutral objects"). As illustrated in Figure 1, each block comprised eight alternating phases of free thinking and suppression (30 seconds each; indicated by a green or red stoplight on the screen, but without any longer displaying the stimulus target item), thus forming a Stimulus type (object vs. chocolate) × Condition (free thinking vs. suppression) design with Condition nested in Stimulus type. Phase shifts (from free thinking to suppression and vice versa) were signaled by an "Attention!" slide (2500 ms) that was preceded and followed by jittered white screens (1800-3000 ms each). After each block, participants rated the percentage of thoughts (i.e., percentage of time they thought about the suppressed item) during free thinking and suppression. Half of the participants started with a chocolate block, the other half with an object block.

--Please insert Figure 1 about here—

[1] Used chocolate pictures: 0083 and 0111; Neutral objects: 1027 and 1151.

The task was presented using Presentation software (Version 14.8, Neurobehavioral Systems, Inc., Berkeley, USA). After the fMRI session, participants rated the four images, which had been shown to them during the fMRI-task, regarding valence ("How pleasant do you find this?" with the anchors “very unpleasant” and “very pleasant” on a 9-point scale) and craving ("How much do you want to have this now?" with the anchors “do not want to have this now” and “do want to have this now” on a 9-point scale). At the end, all participants were debriefed and reimbursed with course credits or 15€.

2.3 Behavioral Data Analysis

All statistical analyses for self-report data were performed using PASW Statistics 21 (SPSS Inc., Chicago, IL, USA). The *cue reactivity hypothesis* predicted two-way interactions of Stimulus type (object vs. chocolate) × Group (low vs. high trait chocolate craving) with valence ratings, craving ratings, and percentage of thoughts as dependent variables in a repeated measures ANOVA. The *suppression failure hypothesis* predicted a three-way interaction of Stimulus type × Group × Condition (free thinking vs. suppression) with the percentage of thoughts as dependent variable in a repeated measures ANOVA. Alpha level for all analyses was set to .05 and significant effects were followed by post-hoc *t*-tests.

2.4 FMRI Recording

MRI data were acquired on a 3-Tesla system (Siemens Magnetom Trio Tim Syngo) with the 12-channel head coil. Three-hundred and four volumes, aligned to the line connecting anterior and posterior commissures, were acquired for each session, and the first five volumes were discarded to allow for stabilization of the blood-oxygen level dependent (BOLD) signal. Functional images were acquired with a T 2 * weighted echo-planar imaging (EPI) sequence (TE= 30 ms, TR=2400 ms, FA=77°, 36 slices with a thickness of 3.0 mm, 192 mm FOV with a 64 × 64 matrix resulting in 3.44 × 3.44 mm in plane resolution). An additional magnetization-prepared rapid-acquisition T1-weighted gradient echo structural image (voxel size of 1 × 1 × 1.3 mm^3) was acquired for co-registration. Participants viewed the experiment through a head-coil–mounted mirror.

2.5 FMRI Data Analysis

Data preprocessing and analysis were performed using SPM12 (Wellcome Trust Centre for Neuroimaging, London, UK). Functional images were slice time corrected to the onset of the middle slice and then realigned and unwarped. It was further checked that the movement parameters were within a maximum of 3mm - a higher deviation led to exclusion. Structural images were segmented and normalized to MNI standard stereotactic space. The resulting parameters were then used for normalization of the previously coregistered functional images, which were resampled to isotropic 3 × 3 × 3 mm^3 voxels and smoothed with a 6 mm full width at half maximum (FWHM) Gaussian kernel. Statistical analysis was performed in a two-stage random-effects model: In the participant-specific first-level model, each block was convolved by a canonical hemodynamic response function and its first temporal derivative. The following block types entered the first-level model: free thinking chocolate, suppression chocolate, free thinking object, suppression object (30 seconds duration each, "Attention" slides modeled with 3 seconds). To deal with residual variance caused by participant movement, the realignment parameters were included as additional regressors of no interest. We then entered the following contrast images (free thinking chocolate, suppression chocolate, free thinking object, suppression object) in a second-level random effects full factorial model with the between-subjects factor Group (low vs. high trait chocolate craving) and the within-subjects factors Condition (free thinking vs. suppression) and Stimulus type (object vs. chocolate). The full-factorial design included following eight columns in the following order (column number in brackets): (1) high trait chocolate cravers free thinking chocolate, (2) high trait chocolate cravers suppress chocolate, (3) high trait chocolate cravers free thinking object, (4) high trait chocolate cravers suppress object, (5) low trait chocolate cravers free thinking chocolate, (6) low trait chocolate cravers suppress chocolate, (7) low trait chocolate cravers free thinking object, (8) low trait chocolate cravers suppress object. The t-contrast weights for the two-way interaction (testing the *cue-reactivity hypothesis*) were: 1 1 -1 -1 -1 -1 1 1 and 1 -1 -1 1 -1 1 1 -1 for the three-way interaction (testing the *suppression failure hypothesis*). We report results corrected for FWE due to multiple comparisons and conduct this correction at the whole-brain level or the peak level within small volume regions of interest for which we had an a priori hypothesis. For analyses of *a-priori* hypothesized brain regions, the threshold was set to $p < .05$ corrected for multiple comparisons (based on the familywise error rate) using reduced search volumes (small volume correction (svc) option within SPM; similar to previous work, Miedl, Büchel, & Peters, 2014; Miedl, Wegerer, Kerschbaum, Blechert, & Wilhelm, 2018). We performed correction for multiple comparisons using spherical search volumes centered at bilateralized peak voxels for the ventral striatum (±12, 10, −8) derived from 671 imaging studies on "reward", as well as bilateralized peak voxels for the dlPFC (±32, 32, 10) derived from 707 imaging studies on "suppression or regulation or craving" as determined by a meta-analysis conducted on the neurosynth.org platform53 (status December 2017; Yarkoni, Poldrack, Nichols, Van Essen, & Wager, 2011) with 10-mm spheres. For putamen/dorsal striatum, correction for multiple comparisons was based on WFU PickAtlas masks implemented in SPM (Maldjian, Laurienti, Kraft, & Burdette, 2003). All activations are displayed projected on the mean structural scan of all participants. Similar to the behavioral analyses, only the 2-way Group × Stimulus type interaction and the 3-way interaction were tested.

3. RESULTS

3.1. Sample Characteristics

High and low trait chocolate cravers did not differ in age, food deprivation (i.e., hours since last meal), or body mass index (Table 1). High compared to low trait chocolate cravers reported much greater trait and state craving for chocolate, as well as higher chocolate liking and consumption (Table 1). Available data of a subset of female participants (24 out of 30) showed that high and low trait chocolate cravers did not differ ($t_{(22)} = 0.276$; $p = .785$) on days since last menstruation. Oral contraceptive usage was 53% for high- and 61% for low trait chocolate cravers.

Table 1

Sample Description with Means (Standard Deviations) of Low Trait Chocolate Cravers (*N* = 20) and High Trait Chocolate Cravers (*N* = 20) and Statistical Comparisons

	Low trait chocolate cravers	High trait chocolate Cravers	Test statistics
Food Cravings Questionnaire-Trait-reduced (chocolate)	**20.5 (7.50)**	**55.6 (10.5)**	***t* = 11.6, *p* < .001, *d* = 3.85**
Age (years)	25.2 (4.64)	26.8 (7.69)	*t* = 0.85, *p* = .404, *d* = 0.25
Body mass index (kg/m²)	21.7 (2.45)	21.9 (2.20)	*t* = 0.28, *p* = .782, *d* = 0.09
Chocolate liking	**45.8 (19.5)**	**91.3 (6.35)**	***t* = 8.69, *p* < .001, *d* = 3.13**
Chocolate consumption (times per week)	**1.07 (0.88)**	**5.63 (1.50)**	***t* = 11.1, *p* < .001, *d* = 3.71**
Food deprivation (hours since last meal)	2.18 (4.06)	2.59 (1.43)	*t* = 0.36, *p* = .725, *d* = 0.13
Food Cravings Questionnaire-State (chocolate)	**23.2 (6.82)**	**48.0 (8.44)**	***t* = 10.2, *p* < .001, *d* = 3.23**

Note: Significant differences are printed in boldface; Chocolate liking ("How much do you like chocolate in general?" was assessed on a scale from 0 (*not at all*) to 100 (*a lot*); the chocolate version of the Food Cravings Questionnaire-State (FCQ-S; Meule & Hormes, 2015) was administered prior to the fMRI-task to assess momentary chocolate craving (Cronbach's $\alpha = .946$).

3.2. Behavioral Results

3.2.1 Cue reactivity hypothesis: Valence and craving ratings

As expected under the cue reactivity hypothesis for *valence ratings*, a significant interaction of Group × Stimulus type, $F_{(1, 38)} = 8.82$, $p = .005$, $\eta_p^2 = .188$ emerged, qualifying main effects of Group, $F_{(1, 38)} = 10.6$, $p = .002$, $\eta_p^2 = .219$, and Stimulus type, $F_{(1, 38)} = 27.3$, $p < .001$, $\eta_p^2 = .418$. High trait chocolate cravers rated chocolate pictures as more pleasant than low trait chocolate cravers, $t_{(38)} = 4.53$, $p < .001$, $d = 1.45$, whereas no differences were found in the object category, $t_{(38)} = 0.57$, $p = .575$, $d = 0.18$ (Figure 2A).

A similar pattern was found for *craving ratings*. The Group × Stimulus type interaction, $F_{(1, 38)} = 29.1$, $p < .001$, $\eta_p^2 = .434$, qualified main effects of Group and Stimulus type, $Fs \geq 29.8$, $ps < .001$. Again, only high trait chocolate cravers exhibited higher ratings than low trait chocolate cravers in the chocolate category, $t_{(38)} = 8.94$, $p < .001$, $d = 2.83$, and no differences were found in the object category $t_{(38)} = 0.99$, $p = .327$, $d = 0.32$ (Figure 2B).

--Please insert Figure 2 about here--

3.2.2 Cue reactivity hypothesis: Percentage of thoughts

The analysis of reported thoughts yielded main effects of Group, $F_{(1, 38)} = 15.0$, $p < .001$, $\eta_p^2 = .283$, Stimulus type, $F_{(1, 38)} = 6.19$, $p = .017$, $\eta_p^2 = .140$, and Condition, $F_{(1, 38)} = 8.12$, $p = .007$, $\eta_p^2 = .176$, as well as two-way interactions (Group × Stimulus type, $F_{(1, 38)} = 11.0$, $p = .002$, $\eta_p^2 = .225$, and Group × Condition, $F_{(1, 38)} = 4.73$, $p = .036$, $\eta_p^2 = .434$), and a three-way interaction (Group × Condition × Stimulus type, $F_{(1, 38)} = 7.51$, p = .009, $\eta_p^2 = .165$).

The Group × Stimulus type interaction supports our *cue reactivity hypothesis*: collapsed across suppression and free thinking conditions, high trait chocolate cravers reported more thoughts about chocolate (M = 28.3, SD = 23.6) than about objects (M = 14.2, SD = 9.69), $t_{(19)} = 3.05$, $p = .007$, $d = 0.78$, whereas low trait chocolate cravers did not differ regarding their percentage of thoughts in the chocolate (M = 6.38, SD = 7.43) compared to the object category (M = 8.41, SD = 6.48), $t_{(19)} = -1.38$, $p = .183$, $d = -0.29$.

3.2.3. Suppression failure hypothesis: Percentage of thoughts

The contrasts following up on the three-way interaction contradicted our *suppression failure hypothesis*: high trait chocolate cravers reported *less* and not more chocolate thoughts during suppression compared to free thinking, $t_{(19)} = -3.01$, $p = .007$, $d = -0.73$. This comparison was not significant for low trait chocolate cravers, $t_{(19)} = -0.21$, $p = .839$, $d = -0.05$ (Figure 3), nor where there any significant suppression effects regarding object thoughts in either group (all ps ≥ .124). The unanticipated ‘successful suppression’ of chocolate thoughts in high trait chocolate cravers motivated an additional post-hoc exploration: suppression of chocolate thoughts in high trait chocolate cravers was successful in being lower than during free thinking but ‘incomplete’ in that they still reported more chocolate thoughts than low trait chocolate cravers during suppression, $t_{(38)} = 2.73$, $p = .010$, $d = 0.86$.

--Please insert Figure 3 about here--

3.3 Neural Results

3.3.1 Cue reactivity hypothesis

In line with the cue reactivity hypothesis, only the left putamen (x, y, z coordinates: -27, 2, 7; z = 5.18) showed stronger activity in high vs. low trait chocolate cravers in the chocolate > object contrast at $p < .05$ FWE-corrected on whole brain level. Comparing low versus high trait chocolate cravers in the reverse contrast (chocolate > object) revealed no significant results. Further exploring *a-priori* hypothesized regions of interest we found a significant effect in the ventral striatum (peak left: −15, 11, −11, $z = 4.50$; $p_{svc} < .001$ FWE corrected; peak right: 15, 14, -8; $z = 3.71$ $p_{svc} = .011$ FWE corrected) and in the right putamen (24, 11, 7; $z = 4.50$; $p_{svc} < .001$ FWE corrected).

--Please insert Figure 4 about here--

3.3.2 Suppression failure hypothesis

Contradicting our hypothesis and the behavioral findings, there was no significant Group × Condition × Stimulus type interaction when examining brain activations at $p < .05$ FWE-corrected on whole brain level and in the dlPFC region of interest.

3.3.3 Auxiliary analysis – Suppression vs. free thinking

Suppression > free thinking activated bilateral occipital/lingual gyrus, whereas the reverse contrast revealed insula, mid-cingulate cortex, precentral and supplementary motor activity (Table 2).

Table 2

Results from the whole brain analysis Suppression vs. Free Thinking. Data are thresholded at $p < 0.05$ (FWE-corrected), with a minimum cluster size of $k = 5$ voxels and MNI coordinates are listed. R: right. L: left.

Region	**Cluster Size, Voxels**	**z Score**	**MNI coordinates (x, y, z)**
Suppression > Free Thinking			

L Occipital Lobe/Lingual Gyrus	38	6.39	-21 -85 -11
R Occipital Lobe/Lingual Gyrus	29	5.81	21 -85 -14
Free Thinking > Suppression			
R Insula	175	7.34	33, 17, 7
		7.01	51, 14, -8
Supplementary Motor Area	372	7.26	0, -1, 61
		6.94	0, 8, 49
Mid-cingulate Cortex		6.13	-9, 14, 37
R Precentral Gyurs	69	6.24	51, -1, 46
		5.36	39, -1, 55
L Insula	96	6.23	-42, 11, -2
		5.79	-33, 11, 7
L Precentral Gyrus	12	5.58	-45, -7, 52

4. DISCUSSION

This study examined one cognitive regulation strategy, thought suppression, as applied to chocolate- and object-related thoughts in a group of high trait chocolate craving individuals relative to a low trait chocolate craving control group. In the context of theories of ironic processes during thought suppression (Abramowitz, et al., 2001; Wegner, et al., 1987) and evidence for enhanced responsiveness to appetitive cues in trait food cravers (Rolls & McCabe, 2007; Ulrich, et al., 2016), two main hypotheses were generated. First, we predicted paradoxical increase of chocolate thoughts under suppression instructions in high trait chocolate cravers (*suppression failure hypothesis)* on the basis of an increased selective reactivity to chocolate stimulation in this group (*cue reactivity hypothesis*).

Cue reactivity is enhanced in high trait chocolate cravers on an experiential and neural level

Results clearly support the cue reactivity hypothesis. Both image-based ratings (valence and craving) and percentage of chocolate vs. object thoughts (collapsed across free thinking and suppression phases of the task) were clearly higher in high trait chocolate cravers. This was not attributable to a generalized reporting bias as the object-based ratings and thoughts did not show such differences. In addition, the brain responses mirrored these data with a remarkable correspondence: particularly striatal areas (dorsal/ventral) selectively showed higher activity in the chocolate relative to the object condition in high trait chocolate cravers.

This finding is consistent with recent studies that investigated implicit and explicit responses towards food (and chocolate in particular) as a function of trait food craving. For instance, a recent study in high and low trait chocolate cravers (Richard, et al., 2017a) included two implicit measures (a Single Category Implicit Association Test and the Affect Misattribution Procedure). Both measures agreed in documenting a selective positive implicit responding towards chocolate in high relative to low trait chocolate cravers. Similarly, Brockmeyer et al. (2015) showed that high trait food cravers displayed an implicit approach tendency towards high-calorie foods in an approach-avoidance task. Moreover, during one week of Ecological Momentary Assessment, it was found that high trait food cravers reported more frequent thoughts about high-calorie snack foods, of which chocolate was the most frequently desired food (Richard, et al., 2017b), indicative of a greater mental elaboration of and/or preoccupation with thoughts about food in individuals with high trait food craving. More generally, implicit responding reflects trait food craving when in an appetitive state (state craving, hunger; Richard, Meule, & Blechert, in revision).

Our neural data complement this picture and hint at the underlying mechanisms. In high trait chocolate cravers, chocolate relative to object-stimulated states went along with relatively higher activity in a network implicated in reward signaling (ventral striatum;

O'Doherty, 2004) as well as habitual reward seeking (putamen/dorsal striatum; Balleine, Delgado, & Hikosaka, 2007; Foerde, Steinglass, Shohamy, & Walsh, 2015). This activation pattern is consistent with several studies on food cue stimulation in relation to chocolate craving (Rolls & McCabe, 2007) and trait food craving in general (Ulrich, et al., 2016), as well as with studies in which availability of foods was manipulated (Blechert, Klackl, Miedl, & Wilhelm, 2016). In contrast to typical passive food-image viewing studies, we found such activity during repeated 30-second blocks of both suppression and free thinking (signaled by traffic lights) and after only a brief pictorial presentation of the cues at block onset. Thus, the observed relative enhancement of activity in high cravers to chocolate most likely reflects sustained mental imagery/cognition. In fact, thought reports documented that high trait chocolate cravers thought of chocolate during an average of 30% of each block (compared to an average of ~6% in low trait chocolate cravers). Such effects might be explained with the elaborated intrusion theory of desire (Kavanagh, Andrade, & May, 2005) which proposes that substance-related intrusions elicit pleasant feelings, which reinforces mental rehearsal of such thoughts. This initial pleasurable rehearsal might explain activity in the reward system areas. In sum, the pattern of brain activity data suggests generally (relative) elevated reward activity level in high trait chocolate cravers.

Chocolate cravers successfully suppress chocolate-related thoughts

To our surprise and contrary to the suppression failure hypothesis, high trait chocolate cravers successfully reduced the time they spent thinking about chocolate in the suppress condition blocks. No such effect was found in low trait chocolate cravers. However, this suppression contrast ‘rides’ on the cue reactivity difference between groups and is, therefore, not fully independent: suppression started from a much higher level in high compared to low trait chocolate cravers and, thus, high chocolate cravers had more ‘room’ to suppress (similar dependencies are inherent to any emotion regulation or craving regulation research). Thought suppression is commonly achieved by invoking unrelated thoughts and clinging to them, that is distraction. Although the present study did not attempt to differentiate between distraction and other potential thought suppression strategies, unstructured comments by the participants suggest the consistent use of distraction (i.e., participants listed thoughts and mental images about future or past events, other people, task-related topics such as traffic lights or other foods, which would be consistent with the activation in visual areas in the suppression > free thinking contrast). Thus, it seems that high trait chocolate cravers were in principle able to use these strategies, despite intermittently returning to their craving thoughts. This is consistent with much of the craving regulation research: top-down regulation strategies such as thinking of long-term consequences (Hollmann, et al., 2012; Kober, et al., 2010; Meule, Kübler, & Blechert, 2013) or imagining the food as unreal (Sarlo, Übel, Leutgeb, & Schienle, 2013) decreased subjective craving measures. Siep et al. (2012) contrasted two downregulation strategies – combined thought/craving suppression and thinking of long-term consequences of palatable food intake (situational reappraisal) – with upregulation and passive viewing conditions while viewing food images on the screen (as opposed to only traffic lights in our study). They found both downregulation strategies equally effective for reducing craving, at least when compared against upregulation (no comparison against passive viewing reported). Interestingly, their suppression condition successfully reduced activity in the ventral striatum and the ventral tegmental area (both left) relative to passive viewing and even outperformed the reappraisal condition in the downregulation of these areas. The authors concluded that (thought) suppression was not so bad after all – at least in the short term. Similar results were reported by Hollmann et al. (2012). However, these fMRI based findings contrast with the two above mentioned EEG studies, reporting mixed findings for the downregulation of long latency event-related potentials (Meule, et al., 2013; Sarlo, et al., 2013).

Turning to the neural correlates of thought suppression in the present study, unexpectedly, there was no change in brain activity as a function of a combination of the factors group, condition, and stimulus type. Thus, the subjectively reported suppression effect in the high chocolate craving group was not accompanied by *differential* neural activity that could be indicative of enhanced or decreased effort/efficiency. Yet, when exploring this main effect we found that (in both groups) suppression activated visual areas – most likely due to target-unrelated mental imagery (Ganis, Thompson, & Kosslyn, 2004) while free thinking activated mid-cingulate cortex and insula, possibly indicative of visceral affective target responses and affective 'relief' from the taxing suppression phases (Critchley, Wiens, Rotshtein, Ohman, & Dolan, 2004). The absence of a group x condition x stimulus type interaction suggests that these regulatory structures were equally engaged in both groups and conditions. In other words, despite more intense cue reactivity in high chocolate cravers, they apparently did not invest more regulation effort than their low craving counterparts. One can thus tentatively conclude that thought suppression was similarly effortful in both groups, although high cravers did not reach the low levels of low chocolate cravers.

Implications for the concept of trait food craving

The present results add to a growing number of studies supporting the validity of the trait food craving concept and its psychometric implementation. On a psychometric level, the present findings suggest that the chocolate version of the FCQ-T-r can predict both chocolate-related cognitions and brain activity. Convergent neural findings have been reported for the general version that does not refer specifically to chocolate (Ulrich, et al., 2016). As shown here and in our Ecological Momentary Assessment study mentioned above (Richard, et al., 2017b), frequent craving-related thoughts seem to characterize this trait, alongside positive implicit evaluation of chocolate cues and striatal activity, supporting the potential utility of these reward-related areas for prospective weight development prediction (Stice & Yokum, 2016). The present study complements this understanding of trait food craving, suggesting that although trait chocolate cravers do think about chocolate more often, cognitive regulation by means of thought suppression is intact and at least partially efficient.

Limitations and nexus with the wider thought suppression literature

Our implementation of the thought suppression task with conditions nested within participants is consistent with much of the craving regulation literature but has only limited comparability with the classical thought suppression studies that assign suppression and free conditions to different participant groups (e.g.; Wegner, et al., 1987). The fact that free thinking and suppression periods alternated without a comparable, non-suppression-'contaminated' baseline, precludes a meaningful investigation of 'immediate enhancement' or 'post-suppression rebound' effects. This is an inherent limitation in within-participant designs, preferred in fMRI research, where conditions are alternated within session. A between-participant or between-session study might solve this problem. This implies that we cannot estimate the number of thoughts that high trait chocolate cravers might have reported 'at baseline', had suppression not preceded it. Thus, the true 'costs' of thought suppression in trait food craving remain to be determined. Furthermore, future studies could contrast distraction with thought suppression to tease these highly related strategies apart. More generally, the results are based on a sample of young students with normal weight, which limits generalizability to individuals with higher age, lower education, under- or overweight, and clinical samples (e.g., individuals with eating or weight disorders). Yet, this limitation applies to many (if not most) other studies in this field and chocolate cravings are highly prevalent in this population (Richard, et al., 2017b). Another limitation pertains to the omission of a measure of actual chocolate consumption. An inclusion of a post-task test meal is recommended for future studies as this could relate thought frequency to actual behavioral control. Moreover, future studies should control for progesterone and estrogen levels, because of its potential influence on reward-related brain activity (Dietrich, et al., 2001; Frank, Kim, Krzemien, & Van Vugt, 2010; Hausmann, Becker, Gather, & Güntürkün, 2002).

Despite these limitations, it can be concluded that trait chocolate craving seems to be characterized by strong bottom-up reward signals and an intact ability to regulate chocolate-related thoughts through thought suppression.

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Compliance with Ethical Standards

Conflict of Interest

The authors declare that they have no conflict of interest.

Informed consent

Informed consent was obtained from all individual participants included in the study.

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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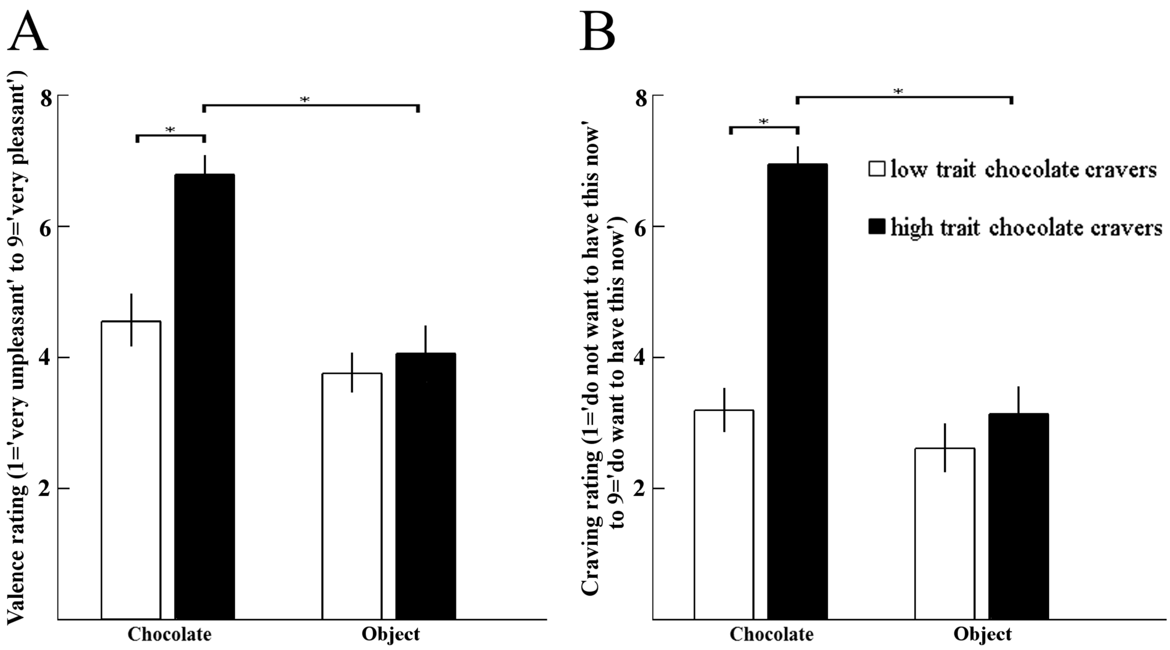
Figure captions:

Figure 1. Illustration of the experimental task.

Figure 2. *Cue-reactivity hypothesis*: Post-fMRI ratings of (A) valence and (B) craving (means, standard errors) as a function of stimulus type (chocolate vs. object).

Figure 3. Percentage of time of chocolate and object thoughts per Condition and Stimulus type, displayed for low and high trait chocolate cravers. Error bars represent standard errors.

Figure 4. Parameter estimates of bilateral ventral striatum (VS; A) and putamen (B) derived from the peak voxels. Error bars represent standard errors (display threshold: $p < .001$ uncorrected; a.u. indicates arbitrary units).


A
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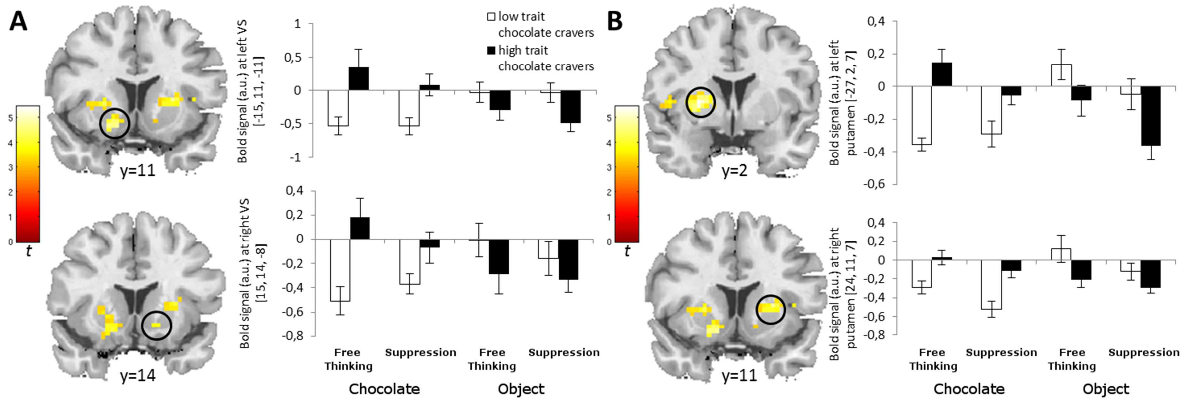
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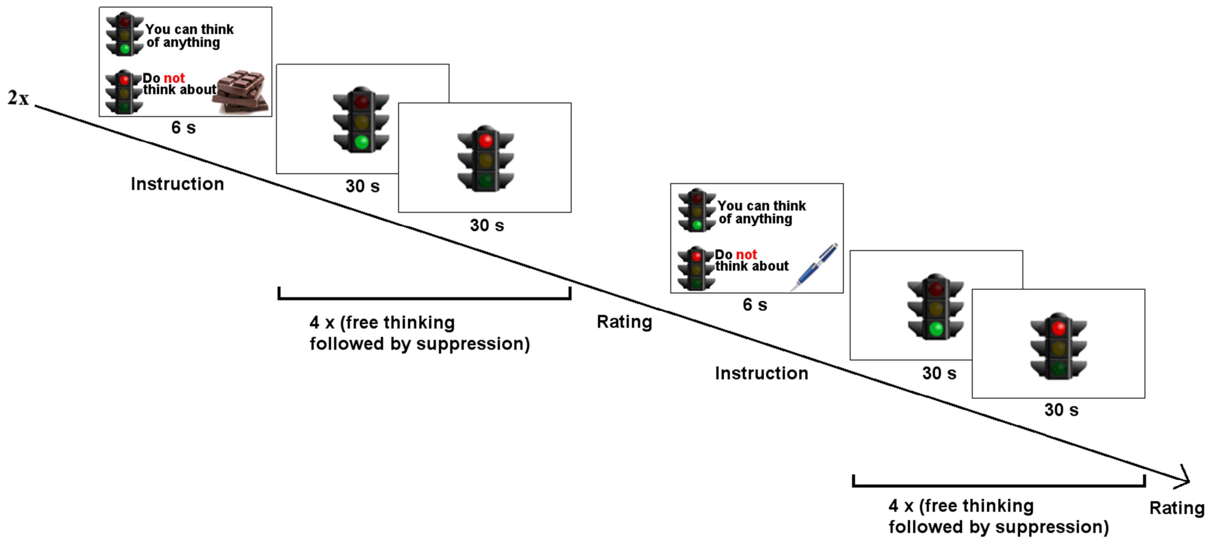

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6 s
Instruction
30 s
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Rating
You can think of anything
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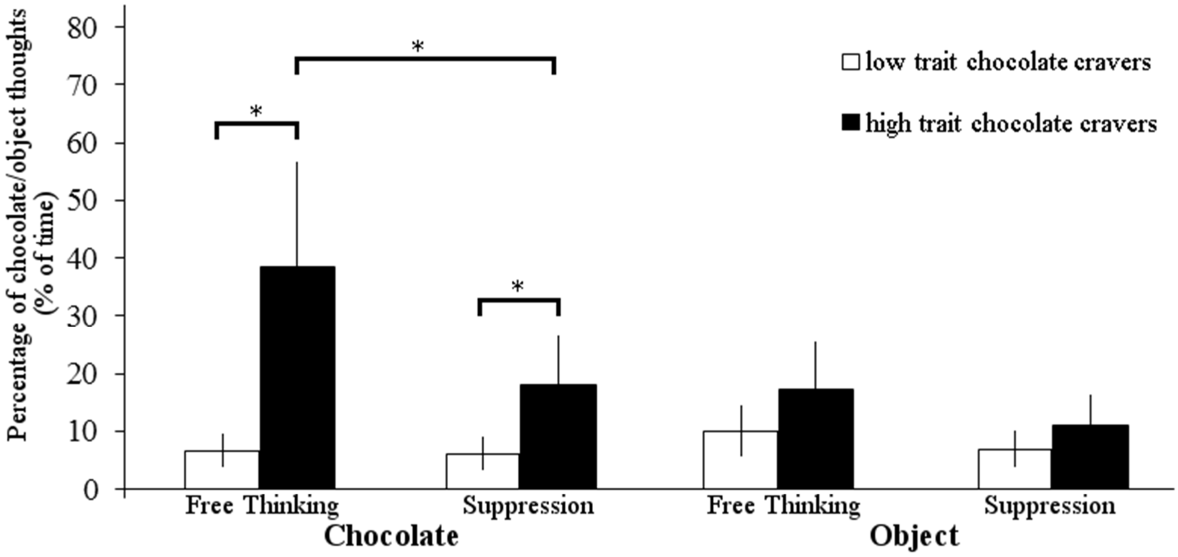
Percentage of chocolate/object thoughts (% of time)
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low trait chocolate cravers
high trait chocolate cravers
Free Thinking
Suppression
Free Thinking
Suppression
Chocolate
Object