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REWARD SENSITIVITY AND SELF-CONTROL IN UNCONTROLLED EATING:
ANALYSIS OF EEG BETA AND THETA DYNAMICS

Master's thesis

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Running head: EEG frequency correlates of uncontrolled eating

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Reward sensitivity and self-control in uncontrolled eating: analysis of EEG beta and theta dynamics

Abstract

The present study investigated the contribution of reward sensitivity (RS) and self-control (SC) to uncontrolled eating (UE) in a non-clinical sample. The EEG of 38 food-deprived female participants was recorded (a) during resting state, (b) while attentively viewing pictures of low-calorie (LC) and high-calorie (HC) foods with matched palatability, and (c) while regulating craving responses to HC food pictures using three common strategies: reappraisal, distraction, and mindful viewing. Activity in the beta and theta frequency bands was used as a correlate of RS and SC, respectively. During the attentive viewing and the three regulation conditions subjective craving ratings were also collected. The Power of Food Scale was used as a trait UE measure. The results showed that women with higher UE may exhibit situationally increased RS, reflected in elevated beta activity during the resting state. Importantly, direct exposure to food stimuli did not further amplify the relationship between UE and beta activity. This pattern indicates that physiological hunger rather than exposure to food cues may be the primary factor in UE-related activation of RS. In the current study, SC markers were not related to UE. SC difficulties may therefore not be an equally important contributor to UE as increased RS in healthy women.

Keywords: uncontrolled eating, Power of Food Scale, reward sensitivity, self-control, EEG, beta, theta

Tasutundlikkuse ja enesekontrolli roll kontrollimatus söömises: EEG beeta ja teeta dünaamika

Kokkuvõte

Käesolevas magistritöös uuriti mittekliinilisel valimil tasutundlikkuse ja enesekontrolli rolli kontrollimatus söömises. Selleks registreeriti 38 näljaseisundis naise EEG (a) puhkeoleku tingimuses, (b) tähelepanelikult võrdselt isuäratavaid kõrge ja madala kalorsusega toitude pilte vaadates ning (c) kõrge kalorsusega toitude piltide poolt tekitatud söömistungi kolme levinud strateegiaga – ümberhindamine, tähelepanu kõrvale juhtimine ja aktsepteerimine – reguleerides. Tasutundlikkuse ja enesekontrolli ajukorrelaatidena kasutati vastavalt aktiivsust beeta ja teeta sagedusribas. Toidupiltide vaatamise ning tungi reguleerimise tingimustes mõõdeti ka subjektiivset söömistungi. Individuaalseid erinevusi kontrollimatus söömises hinnati Toiduvõimu Küsimustikuga. Positiivne korrelatsioon Toiduvõimu Küsimustiku skoori ja puhkeoleku tingimuses mõõdetud beeta aktiivsuse vahel viitab sellele, et kontrollimatut söömist iseloomustab situatiivselt suurenenud tasutundlikkus. Toidupiltide vaatamine Toiduvõimu küsimustiku skoori ja beeta aktiivsuse seost täiendavalt ei suurendanud. Antud tulemused viitavad sellele, et kontrollimatu söömisega seotud tasutundlikkuse võimendumise puhul võib olla keskne roll näljaseisundil, mitte toidustiimulitele eksponeeritusel. Käesolevas uuringus enesekontrolli markerid kontrollimatu söömisega ei seostunud. Sellest võib järeldada, et tervetel naistel ei pruugi enesekontrolli raskused tasutundlikkusega võrdsel määral kontrollimatusse söömisesse panustada.

Märksõnad: kontrollimatu söömine, Toiduvõimu Küsimustik, tasutundlikkus, enesekontroll, EEG, beeta, teeta

Introduction

In modern societies people are almost constantly surrounded by highly palatable energy dense food and food cues. Since appetizing food is naturally rewarding, exposure to food cues triggers food craving (i.e., an intense desire to eat a specific food) that is difficult to resist, thereby often leading to uncontrolled eating (UE; Appelhans, 2009; Kemps & Tiggemann, 2010; Pelchat, Johnson, Chan, Valdez, & Ragland, 2004; Vainik, Neseliler, Konstabel, Fellows, & Dagher, 2015). This is why the term *obesogenic* is often used to describe the modern societies' environment that exerts such strong influence on human eating behavior.

Basic brain systems for food craving and control carry implications for understanding normal and abnormal eating as well as for developing effective techniques to cope with food cravings (Appelhans, 2009; Berridge, 2009; Kemps & Tiggemann, 2010; Pelchat et al., 2004). There is still, however, only limited knowledge about the complex neurobehavioral mechanisms and vulnerability factors related to UE. The present study addresses these issues by exploring the role of food reward sensitivity (RS) and self-control (SC) in a non-clinical sample using EEG frequency correlates.

Food Intake as an Interaction of Appetitive Motivation and Cognitive Control

A common neurobehavioral framework of reward-driven eating describes a dynamic interaction between bottom-up appetitive motivation and top-down inhibitory control (Appelhans, 2009; Siep et al., 2012; Vainik et al., 2015; Van den Bos & de Ridder, 2006). The interplay between these two processes is an influential determinant of food intake.

Bottom-up motivational processes depend on subcortical mesolimbic brain networks (Berridge, 2009; Meule, Kubler, & Blechert, 2013; Siep et al., 2009, 2012). These regions attribute motivational value (i.e., incentive salience) to rewards such as palatable food, and associations are formed with predictive cues. Encountering or simply imagining the sight, smell, or taste of highly valued foods can activate subcortical reward processing related areas (i.e., induce RS response) which is subjectively experienced as food craving (Berridge, 2009; Pelchat et al., 2004).

Craving regulation, on the other hand, is mediated by prefrontal cortex (Appelhans, 2009; Kober et al., 2010). SC can be defined as adjudication between competing action impulses, one of which promises short-term value while the other serves goals with more enduring value (Duckworth & Gross, 2014). SC is frequently needed to balance an immediate food craving with more distal desires to stay healthy and maintain healthy body weight.

Accumulating evidence has shown that food cue elicited subcortical activations and related food craving can be downregulated using cognitive strategies (e.g., Kober et al., 2010; Meule et al., 2013; Siep et al., 2012; Yokum & Stice, 2013).

Individual Differences

People in general demonstrate an attentional bias towards appetizing food and often experience food cravings (Kemps & Tiggemann, 2010; Lowe, van Steenburgh, Ochner, & Coletta, 2009; Nijs, Franken, & Muris, 2008). Nevertheless, some individuals are more prone to problematic overeating (Forman et al., 2007; Lowe, van Steenburgh, et al., 2009). They frequently experience strong motivation to eat even when not being in a state of energy depletion. Despite their long-term health goals, susceptible individuals very often end up consuming far more food than physiologically required, often leading to unhealthy weight gain over time. UE can also lead to symptoms of other psychological conditions, including eating disorders, depression, excessive anxiety, and stress (e.g., Latner, Hildebrandt, Rosewall, Chisholm, & Hayashi, 2007; Touchette et al., 2011).

In terms of the framework presented above, excessive food intake arises when bottom-up processes are too strong and override top-down control, or when control processes are too weak. Some authors have used the term *food-related impulsivity* to describe the interaction between these two trait-like components: increased RS that manifests in the craving for appetitive stimuli, and limited SC that manifests in rash-spontaneous behavior with no regard for the consequences (Dawe & Loxton, 2004; Schag, Schönleber, Teufel, Zipfel, & Giel, 2013). However, after having analyzed the unity and diversity of different eating trait questionnaires, Vainik and colleagues (2015) concluded that different questionnaires capture varying severity of a single latent continuum of UE. Thus, the two mechanisms that have been identified in neurobehavioral research are difficult to distinguish relying merely on self-report measures.

Using EEG to Study Reward Sensitivity and Self-Control

Correlates of neural activity can potentially be used to separate the contribution of RS and SC to UE. EEG frequency dynamics that have been previously associated with the two processes might prove particularly useful.

EEG is the measurement of the ongoing electrical activity of the brain recorded non-invasively from electrodes on the scalp (McLoughlin, Makeig, & Tsuang, 2014). EEG as a

method has several practical research advantages. Being relatively low cost and easy to use, it enables to study larger number of subjects than brain imaging techniques. Furthermore, the excellent temporal resolution of EEG enables analysis of spectral dynamics that are related to emotion, motivation as well cognitive functions (Fries, 2015; Knyazev, 2013). Analysis of event-related spectral perturbations (ERSP) can reveal different aspects of brain function than the traditional ERP (event-related potential) approach (Makeig, Debener, Onton, & Delorme, 2004; Pfurtscheller, 2001). ERPs are sensitive to neural processes that are consistently time-locked to a sensory, motor, or cognitive event. Spectral analyses, by contrast, also capture dynamics that are induced by these events without consistent phase-synchrony (Ertl, Hildebrandt, Ourina, Leicht, & Mulert, 2013; Pfurtscheller, 2001). In addition, spectral analysis allows to decompose the EEG signal into activity in different frequency bands that have been related to different cognitive and affective processes (Fries, 2015; Knyazev, 2013).

Most studies investigating the electrophysiological correlates of RS and SC have focused on analyzing ERPs (e.g., Asmaro et al., 2012; Meule et al., 2013). The few existing ERSP findings suggest, however, a positive relationship between self-reported RS and power in the EEG beta frequency range (around 14-30 Hz) (Hume, Howells, Rauch, Kroff, & Lambert, 2015; Tammela et al., 2010). While the evidence is limited concerning food motivation, the increased beta activity has been repeatedly reported in people with alcohol addiction (e.g., Rangaswamy et al., 2002; Vuong, Xia, Malik, & Rashid, 2013). EEG frequency dynamics in theta range (around 3-8 Hz), on the other hand, have been consistently associated with cognitive control (for a review, see Cavanagh & Frank, 2014; in addition e.g., Ertl et al., 2013; Nigbur, Ivanova, & Stürmer, 2011). These findings give reason to presume that the activity in the beta range and the activity in the theta range could be used to assess the contribution of RS and SC to UE.

Capability Approach to Individual Differences in EEG Frequency Dynamics

A key challenge in studying individual differences with the help of neural correlates involves conceptualizing the underlying interindividual variance. An informative lesson can be drawn from the research of anterior EEG asymmetry which has been linked to individual differences in affective and motivational traits in two types of studies (e.g., Thibodeau, Jorgensen, & Kim, 2006; Tomarken, Davidson, Wheeler, & Doss, 1992). In early studies, asymmetry was generally measured in a resting condition following the *dispositional* conceptualization of traits according to which individuals possess a general tendency to respond in a particular manner across all or most situations (Davidson, 1998). However, despite the extensive pursuit

of linking resting state frontal asymmetry measures to general approach/avoidance tendencies, the findings remained inconsistent and the growing body of research started to suggest the role of situational variables and the relevance of an *interactionistic* approach (Stemmler & Wacker, 2010). Coan, Allen, and McKnight (2006) described the *capability model* of EEG asymmetry claiming that meaningful associations between individual traits and functional brain asymmetry can be captured in trait-relevant situations that actively engage the underlying biological systems. In line with this perspective, specific manipulations as opposed to resting state recordings should be used, and relevant situational and state variables must be considered. The findings from EEG alpha asymmetry studies that have supported the capability approach (e.g., Stewart, Coan, Towers, & Allen, 2014; Uusberg, Allik, & Hietanen, 2015) give reason to suggest that the same principles hold in beta and theta dynamics.

Experimental Investigation of Uncontrolled Eating

The capability approach to studying individual differences requires that the EEG correlates are recorded in conditions and states that are relevant to the construct of interest. For investigating UE, effective and controllable inducement of food craving is crucial. When SC is also of interest, the regulation of craving must be manipulated in a controllable manner.

  Experimental manipulations of reward sensitivity.

There are several ways to experimentally activate RS. In terms of ecological validity, it would be best to use actual food as stimuli (see e.g., Smeets, Roefs, & Jansen, 2009; Tammela et al., 2010) and to manipulate real food availability (e.g., Blechert, Feige, Hajcak, & Tuschen-Caffier, 2010; Werthmann, Roefs, Nederkoorn, & Jansen, 2013). However, there is ample evidence that solely viewing food pictures is sufficient to activate RS and elicit food craving (Tiggemann & Kemps, 2005). Thus, food photographs are most often used as stimuli (e.g., Asmaro et al., 2012; Meule et al., 2013; Siep et al., 2012). In ERP studies, it has been consistently demonstrated that food pictures trigger larger responses reflecting incentive salience of food compared to neutral control stimuli (Nijs et al., 2008).

Excessive food consumption is typically associated with heightened sensitivity to energy dense food (i.e., food high in fat and sugar). The modulating effect of calorie content on food reward processing is often emphasized and associated with attention (Siep et al., 2009; Werthmann et al., 2013). In ERP studies, it has been demonstrated that implicit attentional processes differentiate rapidly food stimuli by calorie content (e.g., Meule et al., 2013; Toepel, Knebel, Hudry, le Coutre, & Murray, 2009). However, it is difficult to distinguish the

effects of calorie density and palatability, as the two often go hand in hand (Siep et al., 2009). There are studies in which little effect of calorie content on food intake has been found when controlling for palatability (e.g., Yeomans, Lee, Gray, & French, 2001). The findings of fMRI studies using food images as stimuli (see e.g., Killgore et al., 2003) have demonstrated the reward-related activation in response to food pictures regardless of the calorie content of depicted foods, as well as calorie specific activation (i.e., calorie content effect) in areas associated with emotion, motivation, and behavioral regulation. Evaluating palatability probably requires more explicit, consciously mediated attentional processes (Killgore et al., 2003). The rewarding value of food depends, to some extent, on co-occurring homeostatic state (Berridge, 2009; Siep et al., 2009). As foods seem more attractive and palatable while being food-deprived, it can be said that the hunger has an enhancing effect on RS response. More importantly, hunger in interaction with calorie content has been shown to affect RS processes (Siep et al., 2009).

To sum up, food pictures can be used to activate RS when investigating UE. Importantly, the modulating effects of calorie content and subjective palatability of depicted food items as well as state hunger need to be taken into account.

Experimental manipulations of self-control.

Instructed cognitive regulation tasks have been shown to modulate subjective food craving and related brain responses (e.g., Meule et al., 2013; Siep et al., 2009) offering an experimentally controllable model of regulation strategies used in daily life. Overall, techniques to cope with craving can be divided into control- and acceptance-based strategies (Forman et al., 2007).

Control-based strategies aim to reduce the frequency and intensity of food cravings (Forman et al., 2007), for instance, by cognitively reinterpreting craving-related thoughts (i.e., reappraisal), thereby altering their emotional/motivational impact. An alternative is to divert attention away from the food stimuli (i.e., distraction). The evidence from experimental studies has demonstrated that both strategies can reduce reward-related brain activity elicited by food stimuli (e.g., Meule et al., 2013; Siep et al., 2012) as well as self-reported food craving (e.g., Giuliani, Calcott, & Berkman, 2013). However, it has been argued that the beneficial effect of using reappraisal and distraction may be restricted to short-term perspective (Forman et al., 2007; Siep et al., 2012).

Acceptance-based strategies, often referred to also as mindfulness-based strategies, are characterized by a distinct perspective and have gained remarkable popularity and research interest during the last decade (Papies, Barsalou, & Custers, 2012). Unlike control-based strategies, coping in accepting/mindful manner does not include the explicit goal of reducing the intensity or frequency of cravings nor relieving associated discomfort (Alberts, Thewissen, & Middelweerd, 2013; Forman et al., 2007). The aim, in fact, is quite the opposite, that is to fully experience cravings without avoidance. To our knowledge, no previous brain imaging or EEG study has investigated the effects of mindfulness-based strategies in the context of food-craving regulation. However, mindful attention has been shown to reduce both self-reported craving and related brain activity in smokers (Westbrook et al., 2013). Furthermore, there is some experimental evidence that brief mindfulness instruction can reduce calorie intake compared to distraction (Arch et al., 2016). Mindfulness-based strategies are considered very promising for coping with food craving, especially in a longer perspective and particularly for vulnerable individuals (Forman et al., 2007).

Given their unique effectiveness profiles both control- and mindfulness-based strategies merit attention when studying the role of SC difficulties in UE.

Present Study

With the present study, our aim was to investigate the electrophysiological correlates of uncontrolled eating (UE) in a sample of healthy women. More specifically, we used EEG frequency dynamics to differentiate whether and to what extent RS and SC contribute to UE. While the dual process conceptualization is in line with neural and behavioral data (Appelhans, 2009; Vainik et al., 2015), the mechanisms of reward sensitivity (RS) and self-control (SC) are difficult to distinguish relying solely on self-report questionnaires (Vainik et al., 2015). We used The Power of Food Scale (PFS, Lowe, Butryn, et al., 2009) as a self-report measure of trait UE. The higher PFS score has been frequently associated with higher sensitivity to the appetizing food and thus the vulnerability to UE-related problems (Forman, Hoffman, Juarascio, Butryn, & Herbert, 2013; Lowe & Butryn, 2007). Although there are many potential measures of UE, we preferred PFS because it has reliably demonstrated sensitivity to individual differences in non-clinical range, capturing UE of intermediate severity on the proposed continuum (Davis, 2013; Vainik et al., 2015). Previous research has suggested that RS may be reflected in EEG beta dynamics (Hume et al., 2015; Tammela et al., 2010) and SC in theta dynamics (Cavanagh & Frank, 2014; Ertl et al., 2013; Nigbur et al.,

2011). We therefore used the modulation of beta and theta activity as RS and SC markers, respectively, having beforehand controlled that our analyses supported that decision.

We measured the EEG of healthy food-deprived female participants in (a) resting state before the experiment, while (b) attentively viewing pictures depicting appetizing food items with either high (HC) or low (LC) calorie content, and (c) while regulating craving in response to HC food pictures using three common regulation strategies – distraction, reappraisal, and mindful viewing. During the attentive viewing and the regulation conditions subjective craving ratings were also collected.

We expected that the hypothesized relationship between UE and RS or SC is captured by the stronger association between PFS score and beta or theta activity, respectively. According to the capability model (Coan et al., 2006), the relationships should be revealed only when RS and SC are activated in a manner that exposes respective UE-related differences (i.e., increased RS and reduced SC). Specifically, three possibilities may hold: (1) UE-related RS activation is revealed in the state of hunger, (2) UE-related RS is activated when hungry participants are attending to appetizing HC food stimuli, (3) UE-related SC is activated when participants exert regulation strategies in response to food craving elicited by palatable HC food pictures. To confirm the importance of state hunger and other food-study specific contextual variables as well as to rule out the context-independent dispositional relationship between beta/theta and UE, we conducted supplementary analyses using control data. That is, we investigated correlations between PFS and resting-state EEG from separate experiments not associated with food/eating context, and in which the participants were not in a food-deprived state.

The main hypotheses we tested are as follows:

1. UE is associated with increased RS in the state of hunger. This should be reflected in a positive correlation between PFS score and beta activity during resting state when food-deprived participants are expecting to be exposed to food stimuli. To confirm the relevance of hunger state and situational influences (i.e., the context of participation in food-related study), resting state beta activity was correlated with PFS score also in a control sample where no significant association was expected.

2. UE is associated with increased RS when exposed to HC but not LC food cues. Thus, calorie content effect should be reflected in an interaction between PFS and beta in response to HC (cf. LC) food pictures.

3. UE is associated with reduced SC. This should be reflected in the negative association between lower overall theta activity and higher PFS score and/or lower theta activity in regulation conditions for these participants with higher PFS score.

Method

Participants

Participants were recruited from a larger pool of respondents to an online survey (for further details, see Vainik et al., 2015). The final sample consisted of 38 female volunteers (age range 19-54 years, *M*= 29.21, *SD*= 10.08). The BMI ranged from 17.3 to 43.4 kg/m^2 (*M*= 23.26, *SD*= 5.65). Exclusion criteria were participation in the prior stimulus validation study, left-handedness[1], vegetarianism, regular use of psychoactive medication, pregnancy, breast-feeding, weight fluctuations more than ±5 kg during the last 5 months, and scoring above the cutoff for clinical eating disorders on the Eating Disorders Assessment Scale (Akkermann, 2010), that is none of the participants met the criteria for eating disorder diagnosis. Of the 42 initial participants, 4 were excluded for excessive EEG artifacts or recording problems (see subsection **EEG Recording and Preprocessing**). Undergraduate participants taking psychology courses at the University of Tartu received research participation credit. The others participated in a drawing of a bookstore gift cards. Written informed consent was obtained from all participants. The study was approved by the Research Ethics Committee of the University of Tartu.

Control sample.

The control sample consisted of 33 female participants who had taken part in different cognitive/affective EEG experiments (i.e., absence of food context and state hunger). Age range was 19-30 years, *M*= 22.21, *SD*= 5.17. The BMI ranged from 17.4 to 37.6 kg/m^2 (*M*= 22.48, *SD*= 4.16).

Stimuli

We first composed and validated a new stimuli collection. For enabling us to make the planned comparisons (see subsection **Present Study**), it was necessary to have one picture set depicting LC food items and four sets depicting HC food items. All four sets of HC stimuli needed to be distinct but comparable (i.e., across all HC sets pictures of the same food

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[1] One participant was left-handed. We decided that she can remain in a sample after having controlled that her data did not produce any confounding effects.

categories had to be visually as similar as possible in photographing angle, size, position, details, and background). The single LC stimuli set had to include visually comparable alternatives to HC food categories. Following these guidelines, freely accessible food photographs were searched and downloaded from the Internet.

The stimuli pool was validated in a web-based pilot study in which four independent samples (in sum 234 participants, 83.3% female) rated the palatability and healthiness of 208 food pictures. The subsamples were comparable by the proportion of male and female participants ($\chi^2_{(2, N=234)}$=2.10, p=0.55), age ($F_{(3,230)}$=0.22, p=0.88, η_p^2=0.00; across all samples: M=29.18 years, SD=9.09,), BMI ($F_{(3,229)}$=0.66, p=0.58, η_p^2=0.01; M=22.24 kg/m^2, SD=4.59), subjective hunger ($F_{(3,230)}$=0.58, p=0.63, η_p^2=0.01; hunger was rated on a Likert-type scale 0-*not at all hungry* to 6-*very hungry*, M=3.85, SD=1.92) and time since last meal ($F_{(3,230)}$=0.76, p=0.52, η_p^2=0.01; M=3.01 hours, SD=3.37). We arranged the five stimuli sets in a way that all 5 (i.e., 4 HC and 1 LC) were comparable by the mean palatability rating (M=3.59, SD=0.41, $F_{(4,65)}$=0.07, p=0.99, η_p^2=0.00), but while the four HC blocks had comparably low mean healthiness rating (M=1.78, SD=0.64, $F_{(3,52)}$=0.01, p=0.99, η_p^2=0.00), the mean healthiness rating was significantly higher in LC block (M=4.68, SD=0.53, $F_{(4,65)}$=58.91, p<0.001, η_p^2=0.78).

The final stimuli collection included in sum 70 pictures of different category food items (14 LC and 56 HC, equal number of sweet and savory foods)[2]. Importantly, the actual calorie content of represented foods was not controlled. Since it is well known that the physical parameters of visual stimuli can influence EEG responses (Delplanque, N'diaye, Scherer, & Grandjean, 2007), the variation in spatial frequency and luminance measures of all stimuli sets were statistically controlled. Sample pictures from our stimuli collection are demonstrated in **Figure 1**. Further details about the validation study sample and stimuli sets are available in previous report (Arras, 2014).

Individual Difference Measure – The Power of Food Scale

Uncontrolled eating was measured with the Power of Food Scale (Lowe, Butryn, et al., 2009), a frequently used 15-item self-report questionnaire that captures individual differences in

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[2] Food categories represented in stimuli pictures were as follows: (1) **HC-savory**: "French fries", "chicken drumsticks", "baked potatoes", "lasagna", "pasta", "pizza", "grilled sandwich"; (2) **HC-sweet**: "chocolate bar1", "chocolate bar2", "cheesecake", "chocolate candies", "cookies", "pastry", "chocolate cake"; (3) **LC-savory**: "grilled vegetables", "vegetable puree soup", "Greek salad", "cucumber", "green beans", "filled zucchini", "radish mini sandwich"; (4) **LC-sweet**: "banana slices", "cherries", "poached pears", "raisins", "apple", "pear", "fruit salad".

appetite-related thoughts, feelings and motivations in environments where plentiful palatable foods are constantly available. PFS items are presented on 5-point Likert-type scale with responses ranging from 1-*do not agree at all* to 5-*strongly agree*. Although the majority of items focus on eating-related thoughts and feelings (e.g., "*I think about food even when I am not hungry* ", "*I think that I enjoy eating more than most other people do*") rather than actions, there are also some items that imply directly the loss of control (e.g., "*It's scary to think about the power that food has over me*", „*I love the taste of certain foods so much that I cannot avoid eating them, even when they are unhealthy*"). Participants completed the PFS online, prior to the experiment, as a part of a larger online study. Details about the Estonian version of PFS are provided in Vainik et al. (2015).

Figure 1. Examples of stimuli pictures used in the experiment.
Panel **A** illustrates the *calorie contrast*. In the upper row: 2 categories of HC savory and sweet foods. In the lower row: 2 categories of LC savory and sweet foods. Panel **B** illustrates the *regulation contrast*. Two rows of 4 similar pictures depict 2 categories of HC savory and sweet foods. Each of 4 pictures from one category was presented in different condition (attentive viewing HC, distract, reappraise, mindful viewing).

Procedure and Design

The overview of all study procedures and experimental design are summarized in **Figure 2**.

Experimental procedures started at 9 am and lasted approximately 3 hours. Participants had been requested to abstain from any food and drinking beverages other than water in the morning before the experiment, so that they would be in a roughly comparable hunger state at the time of testing. On arrival to the laboratory, a general overview of the procedure was provided and written informed consent was obtained. Participants assessed their pretest subjective hunger on a visual analogue scale (*not at all hungry – very hungry*) and were seated in a comfortable chair in sound-attenuated room. While EEG electrodes were being attached, all participants were served individually measured portion of either apple or banana. The serving of preferred fruit amounted to 5% of personally calculated daily estimated energy requirement[3]. General information was provided about EEG measurement and participants were instructed to sit as relaxed and quietly as possible during the experiment, keep their gaze on the screen during picture presentation, and avoid excessive movements and facial expressions. The stimuli were presented on a 19-inch computer screen at a viewing distance of approximately 114 cm from the subjects' eyes. During measurements, the room was dimly lit and quiet, and the experimenter was in the other room.

First, 6 minutes of resting-state EEG was recorded at 1-minute intervals during which participants either viewed the fixation cross in the middle of the screen or held their eyes closed.

The experiment consisted of four different conditions in separate blocks. In the ATTENTIVE VIEWING condition, the participants were asked to focus their attention on the LC and HC food pictures, that is simply view the depicted food items while trying to take notice of all qualities and details. In case participants noticed other thoughts interrupting, they were simply asked to bring their attention back to the stimuli. The other three conditions entailed specific regulation strategies and only HC food items were presented.

In DISTRACT condition, participants' attention was diverted to unrelated aspects of depicted foods to cognitively distract them from food craving. Specifically, the participants were asked

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[3] We used the following equation: $EER=[354-(6.91\times age)]+PA\times[(9.36\times weight)+(726\times height)]$, in which EER-estimated energy requirement and PA- physical activity coefficient. More information about the calculation is available from http://www.globalrph.com/estimated_energy_requirement.htm.
PA was assessed according to the suggestions from Johansson & Westerterp (2008).
Estimated energy content of banana and apple was obtained from http://ndb.nal.usda.gov/ndb/search/list.

to first label the food item they saw and then to repeat silently different first names that start with the same letter as the food they were viewing (e.g., "pizza" – "Paul, Patrick, Peter, etc."). Participants were asked to continue to repeat the names as long as the food picture was on the screen.

In REAPPRAISE condition, participants' task was to reduce the subjective craving by thinking about different negative consequences of eating HC foods they were viewing. The harmful consequences could be immediate (i.e., feeling uncomfortably full, exhausted, nauseous, ashamed, or guilty etc.) or long-term (i.e., gaining weight, unwanted influences on body shape, physical fitness, and health etc.). The participants were asked to think about these consequences that were most important to them personally, and to convince themselves about the seriousness of these unwanted outcomes.

In MINDFUL VIEWING condition, participants were not asked to effortfully down-regulate the craving. Instead they were instructed to pay attention to their inner experience while they were viewing the food pictures. They were asked to notice all arising emotions, thoughts, and bodily sensations in an accepting manner without trying to change them. Rather than trying to control the experience, participants were suggested to simply observe what was going on in their mind and body, as like from bystander perspective.

For all participants, the experiment began with the ATTENTIVE VIEWING block, followed by the three regulation blocks – DISTRACT, REAPPRAISE, and MINDFUL VIEWING – in randomized order. In each of the three blocks there were three repetitions of stimuli in pseudorandomized order. The pairing of three HC stimuli sets and regulation conditions was counterbalanced across participants. There were short resting pauses with participant-controlled length within each block. Each block began with written and oral instructions. Prior to each experimental block, participants were trained in the use of regulation strategies during practice trials with images not included in the experiment. The experimenter provided dynamic feedback and shaped the use of the strategies when it was necessary. The measurement began once the experimenter was convinced that the participant understood the instructions. At the end of each block, participant answered self-report manipulation check questions about following the instructions.

RECRUITMENT

Participation in a larger online survey* where respondents filled in, among others, the following questionnaires:

Power of Food Scale (PFS)
Eating Disorders Assessment Scale (EDAS)

Recruitment based on EDAS cut-off score (i.e., do not meet the criteria for eating disorder diagnosis)
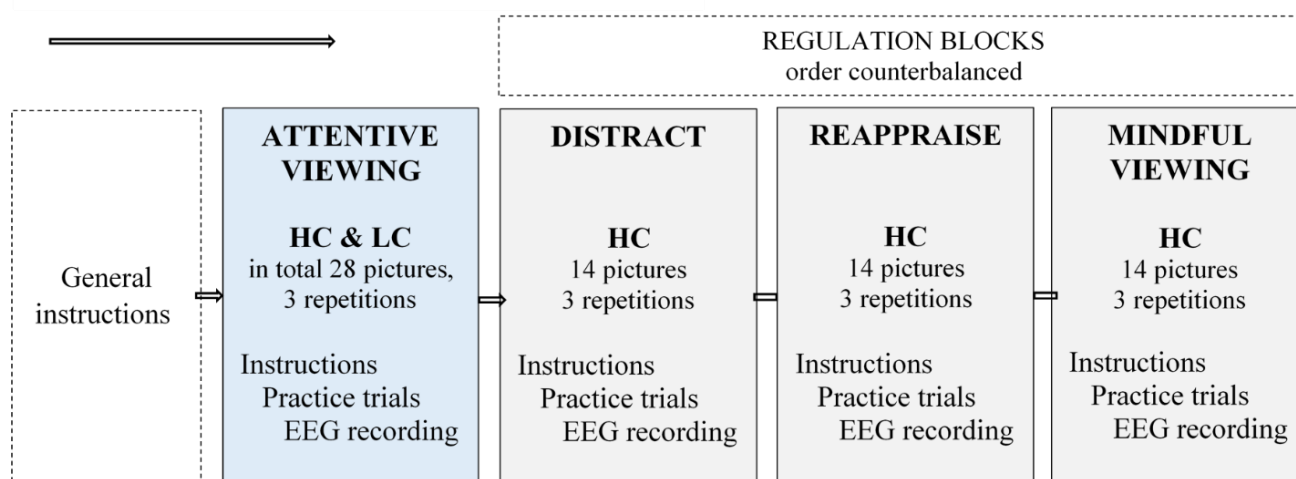
BEFORE EXPERIMENT

Requirement not to eat in the morning

Preparations in the lab & eating pre-measured portion of banana/apple

Resting state EEG recording (6 minutes)

EXPERIMENT: DESIGN & PROCEDURES

REGULATION BLOCKS
order counterbalanced

General instructions	**ATTENTIVE VIEWING** HC & LC in total 28 pictures, 3 repetitions Instructions Practice trials EEG recording	**DISTRACT** HC 14 pictures 3 repetitions Instructions Practice trials EEG recording	**REAPPRAISE** HC 14 pictures 3 repetitions Instructions Practice trials EEG recording	**MINDFUL VIEWING** HC 14 pictures 3 repetitions Instructions Practice trials EEG recording

AFTER EXPERIMENT

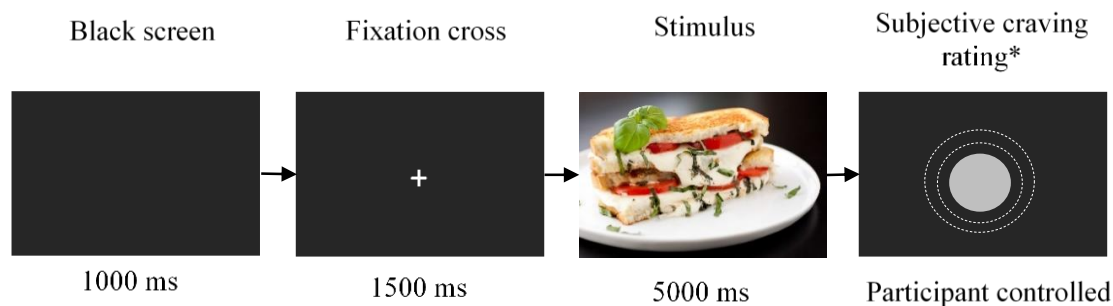**Resting state EEG recording** (6 minutes; not analyzed in the current study)

Post-experiment survey

Figure 2. Overview of all study procedures and experimental design. *For more information, see Vainik et al. (2015).

On each trial (illustrated in **Figure 3**), the participants first saw black screen for a 1000 ms, then a fixation cross for 1500 ms, followed by the stimulus for 5000 ms. In all experimental blocks, we asked participants to provide us with the subjective craving ratings by reporting how much of the food just seen they would like to eat right now if they could (imagining that the food they viewed was the only food they can eat in the next three hours). The craving ratings were reported once about every picture, randomly after its first, second, or third

presentation on a circle-shaped visual analogue scale (imitating a plate), the size of which subjects could change with a computer mouse. The participant answered the question: "*How big of a plate of this food would you want to eat right now*?". In case the participant did not eat the certain food or did not want it at all they were told to leave the circle in a minimal size and move on. The duration of time for giving an answer was under participants' control.

Black screen	Fixation cross	Stimulus	Subjective craving rating*
1000 ms	1500 ms	5000 ms	Participant controlled

Figure 3. Trial sequence. * "*How big of a plate of this food would you want to eat right now*?"

At the end of the experimental manipulations, the resting-state EEG was measured once again (data not analyzed in the current study). Then, the electrodes were removed and lastly, participants filled in the post experiment self-report questionnaire that covered questions about implemented strategies more in detail, as well as the other relevant questions regarding the study. Finally, the participants were debriefed about the goals of the study.

EEG Recording and Preprocessing

A *BioSemi Active Two* (BioSemi, Amsterdam, Netherlands) active electrode system was used to record signals from 32 scalp locations, two reference electrodes placed on earlobes and four ocular electrodes (above and below the left eye and near the outer canthi of both eyes). The continuous data were recorded at 512 Hz sampling rate. Offline preprocessing was conducted using EEGLAB (Delorme & Makeig, 2004) and Matlab (MathWorks, USA) software. Data were first down-sampled to 256 Hz and re-referenced to linked mastoids. Eye-movement artifacts (the activity related to blinks, vertical or horizontal eye movements) were corrected using Independent Component analysis (ICA) algorithm and automatic segment removal. The continuous data were high-pass filtered at 1 Hz and low-pass filtered at 40 Hz. Then, the data was cut into 6.5-second epochs (1500 ms pre-stimulus to 5000 ms post-stimulus) and the mean voltage of the pre-stimulus period was removed as baseline. Finally, the threshold based artifact rejection was implemented. All segments where voltage fluctuations from the baseline exceeded ±100 µV were marked as artifacts. If a single channel was exclusively responsible

for more than 2% of trials being marked for rejection, the channel was rejected before rejecting any epochs. In order to be included for data analysis, a participant's dataset needed to retain an average of at least 8 of 14 trials (>57%) from each condition.

The resting data were preprocessed using a similar pipeline on 1-second epochs with the following differences. Epoch mean instead of pre-stimulus mean was removed as baseline for resting epochs. Only 1 Hz high-pass filtering was used. Artifacts were screened with EEGLAB 'rejspec' algorithm (15-30 Hz, ±45dB) instead of the threshold algorithm.

Average baseline-corrected spectral power estimates (ERSPs) were calculated using wavelet analyses of frequencies between 3 to 30 Hz (EEGLAB 'newtimef' function). The number of Morlet wavelet cycles was adjusted to the frequency band being analyzed starting from 3 cycles at the lowest to 33.3 cycles at the highest frequency yielding a consistent sampling window of 1000 ms. The resulting estimates had 50 ms temporal and 1 Hz frequency resolution. Power estimates were normalized by dividing power estimates within a single trial with the trial mean in each frequency. Estimates were then baseline-corrected by dividing the post-stimulus power by mean pre-stimulus power (1500 ms pre-stimulus to 0 ms) within each frequency band. ERSPs were averaged within two frequency windows: beta (16-21 Hz) and theta (3-6 Hz). Based on visual inspection of the distribution of beta and theta dynamics, the signal was further averaged within spatial ROI (i.e., region of interest) which for beta was defined as C3, CP1, Cz, FC1 (central, slightly left-lateralized) and for theta AF3, AF4, Fz (midfrontal). Finally, based on graphical presentation of the omnibus results of the mass univariate ANOVA of averaged perturbations, we decided the time-windows for beta and theta as follows. That is, beta perturbations were averaged within 800-3300 ms and theta perturbations within 890-4000 ms.

Analyses

Pearson correlation coefficients were calculated between the sum score of PFS and resting-state beta and theta activity in the main sample as well as in the control sample.

Remaining statistical inferences were based on a linear mixed-effect regression (LMER) analyses. We conducted three similar models to predict three dependent variables: (1) event-related spectral beta activity, (2) event-related spectral theta activity, and (3) subjective craving. Subject and item (i.e., picture content) were included as random effects. Fixed effects were the total score of PFS, experimental condition and their interaction. We used restricted

maximum likelihood (REML) estimator to fit our models, as this is recommended for small sample sizes.[4]

First, we checked whether the assumptions of LMER were satisfied. Using the function 'mcp.fnc' (from R package "LMERConvenienceFunctions"; Tremblay, University, Ransijn, & Copenhagen, 2015) we graphed three plots and controlled that the following prerequisites were met: (1) normality of residuals (i.e., model residuals were roughly normally distributed), (2) linearity (i.e., the actual standardized residuals and theoretical quantiles followed linear pattern), and (3) homoscedasticity (i.e., the residuals of our models had roughly a similar amount of variance from predicted values).

We tested whether our model revealed a significant effect of PFS, condition and/or PFS*condition interaction. Satterthwaite approximation was used to obtain standard errors of estimates and perform standard statistics on LMER estimates. Depending on which effects were found to be significant, we constructed simplified models using only significant effects to better understand the contrasts we had defined beforehand. As an effect size measure suitable for small sample sizes we report omega squared (Ω_0^2) statistic. There were 4 different contrasts, one of which was *calorie contrast* (i.e., contrasting the brain responses in attentive viewing HC and attentive viewing LC conditions), and the remaining three were *regulation contrasts* (i.e., contrasting attentive viewing HC with distract, reappraise and mindful viewing conditions). In addition, scatterplots and regular regression lines were used to understand and visualize the continuous variable effects.

Additionally, to test the possible association between beta and theta activity, Pearson correlation coefficients were conducted between beta and theta activity in resting state and between mean beta and theta ERSP of each participant in each condition during the experiment.

All statistical analyses were performed in R environment (R Core Team, 2017). We used the following R packages: 'lme4' (Bates et al., 2016), 'lmerTest' (Kuznetsova, Brockhoff, & Christensen, 2016) and 'sjPlot' (Lüdecke & Schwemmer, 2017).

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[4] Formula we used to conduct LMER models in R were as follows:
(1) lmer (subjective craving ~ PFS * condition + (1|subject) + (1|picture), data = D3s, REML = 1);
(2) lmer (beta ERSP ~ PFS * condition + (1|subject) + (1|picture), data = D3s, REML = 1);
(3) lmer (theta ERSP ~ PFS * condition + (1|subject) + (1|picture), data = D3s, REML = 1).

Results

The results of 3 LMER models predicting (1) beta ERSP, (2) theta ERSP, and (3) subjective craving are summarized in **Table 1**. The results of simplified LMER models including only significant effects from full model are summarized in **Table 2**.

Table 1
Standard experimental effects on dependent variables.

1.1.Experimental effects on the mean beta ERSP

	df1	*df2*	*F*	*p*
PFS	1	36.03	0.98	0.33
Condition	4	171.24	23.36	**<0.001**
PFS*condition	4	2542.00	1.07	0.37

1.2.Experimental effects on the mean theta ERSP

	df1	*df2*	*F*	*p*
PFS	1	35.87	0.24	0.63
Condition	4	165.95	20.28	**<0.001**
PFS*condition	4	2534.71	0.80	0.53

1.3.Experimental effects on the mean subjective craving

	df1	*df2*	*F*	*p*
PFS	1	36.01	2.10	0.16
Condition	4	101.78	19.24	**<0.001**
PFS*condition	4	2542.01	5.61	**<0.001**

Notes: Satterthwaite approximation used for degrees of freedom and *p*-values. Statistically significant *p*-values are in bold.

Table 2
Linear mixed-effect regression models including only significant effects from full models.

Fixed parts	Model 1 Beta ERSP			Model 2 Theta ERSP			Model 3 Subjective craving		
	B	CI	p	B	CI	p	B	CI	p
(Intercept)	0.00	-0.14 – 0.14	.99	0.00	-0.06 – 0.06	.99	0.00	-0.26 – 0.27	.97
PFS							0.14	-0.05 – 0.32	.16
Attentive view. LC	-0.09	-0.21 – 0.03	.16	0.12	-0.00 – 0.24	.06	0.31	-0.01 – 0.63	.07
Distract	-0.47	-0.58 – -0.36	**<.001**	0.52	0.40 – 0.63	**<.001**	-0.15	-0.23 – -0.07	**<.001**
Reappraise	-0.34	-0.44 – -0.23	**<.001**	0.15	0.03 – 0.27	**<.05**	-0.28	-0.36 – -0.20	**<.001**
Mindful viewing	-0.33	-0.43 – -0.22	**<.001**	0.21	0.09 – 0.33	**<.001**	0.03	-0.05 – 0.11	.49
PFS*attentive view. LC							-0.14	-0.22 – -0.06	**<.01**
PFS*distract							-0.01	-0.09 – 0.08	.87
PFS*reappraise							0.01	-0.07 – 0.09	.84
PFS*mindful							0.05	-0.04 – 0.13	.28
Random parts									
σ^2	0.79			0.95			0.46		
$\tau_{00, subject}$	0.18			0.02			0.34		
$\tau_{00, picture}$	0.01			0.00			0.18		
$N_{subject}$	38			38			38		
$N_{picture}$	28			28			28		
$ICC_{subject}$	0.19			0.02			0.34		
$ICC_{picture}$	0.01			0.00			0.18		
Observations	2614			2614			2614		
Ω_0^2	.22			.06			.55		

Notes: σ^2 – within-group random effect variance; τ_{00} – between-group random effect variance; **ICC** – intra-class correlation coefficient that can be interpreted as the proportion of variance explained by random factor; Ω_0^2 – effect size measure, estimating how much variance in dependent variable is accounted for by predictive variables.
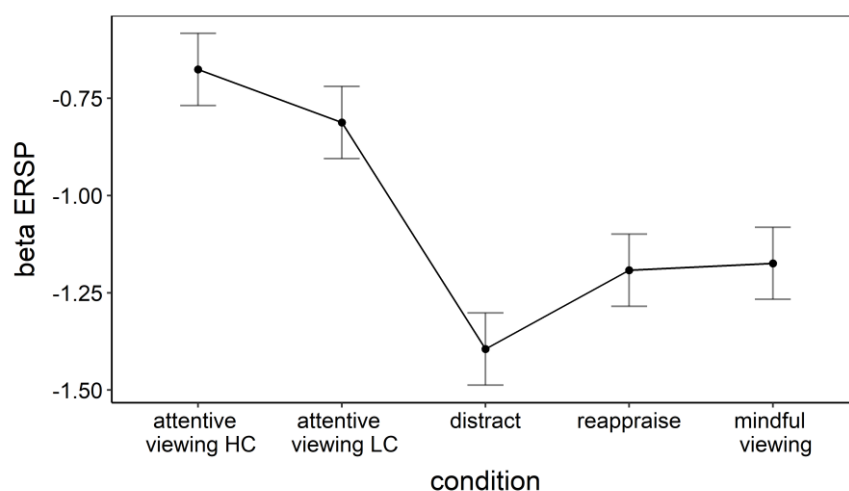All statistically significant p-values are in bold.

Within-Subject Experimental Effects

   Beta as reward sensitivity correlate.

We first tested whether our data revealed a calorie contrast effect in attentive viewing of HC compared to LC food pictures. That is, we expected to see stronger beta activity in response to HC stimuli. However, we did not find such result. LMER analysis of beta ERSP revealed that the mean beta response was at comparable level in attentive viewing HC and attentive viewing LC conditions (see **Table 2**).

However, compared to attentive viewing of HC pictures, all three regulation strategies lowered beta activity significantly (in all cases: $p<0.001$). From **Table 2**, β values show that beta activity decrease (cf. attentive viewing HC) was largest when participants exerted distraction, following reappraisal, and the difference was smallest as a result of mindful viewing. **Figure 4** illustrates the mean beta power in different conditions. The overall simplified beta LMER model, including only condition as significant fixed factor, explained (Ω_0^2) 22% of beta variance. ICC-s showed that subject as random factor explained 19% and picture content as random factor 1% of beta variance.
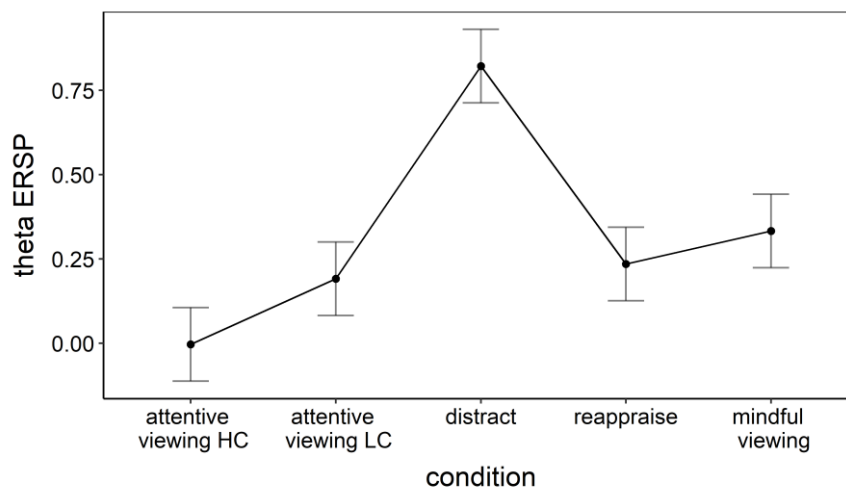

Figure 4. Mean beta ERSP in different conditions. Error bars depict Least Significant Difference. Mean outside the range is significant.

Additional LMER model[5] with subjective craving as dependent variable revealed that beta activity significantly predicted self-reported subjective craving ($F_{(1, 181)}$=11.50, $p<0.001$). Specifically, according to β values, when beta power increased 1 SD, subjective craving was enhanced 0.22 SD. The model explained (Ω_0^2) approximately 78% of subjective craving's variance.

To conclude, despite the lack of calorie contrast effect, power in the beta frequency band seems to coincide with food craving and can be considered a correlate of RS.

Theta as self-control correlate.

LMER analysis of theta ERSP revealed that compared to attentive viewing of HC pictures, the mean theta power in all regulation conditions was significantly higher. According to β values (see **Table 2**), theta activity was highest in distraction ($p<0.001$), but compared to attentive viewing HC also significantly higher in mindful viewing ($p<0.001$) and reappraisal ($p<0.05$). In the latter two conditions, theta power was comparable. Concerning theta power in attentive viewing HC and LC contrast, the trend towards higher theta in response to LC food pictures was found ($p=0.06$). **Figure 5** illustrates the mean theta power by condition. The simplified model, including only condition as significant fixed factor, explained (Ω_0^2) only 6% of theta ERSP variance. ICC-s showed that subject as random factor explained 2% and picture content as random factor less than 1% of theta variance.

Figure 5. Mean theta ERSP in different conditions. Error bars depict Least Significant Difference. Mean outside the range is significant.

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[5] The differences from the main LMER models were as follows. Event-related beta was included as fixed effect and subject as random effect [lmer (subjective craving ~ beta_ersp + (1|subject), data = D2s, REML = 1)]. The between-subject variability in subjective craving ratings' variability was omitted. Similarly, as beta power was baseline-corrected, the individual variability in general beta power did not confound the analysis.
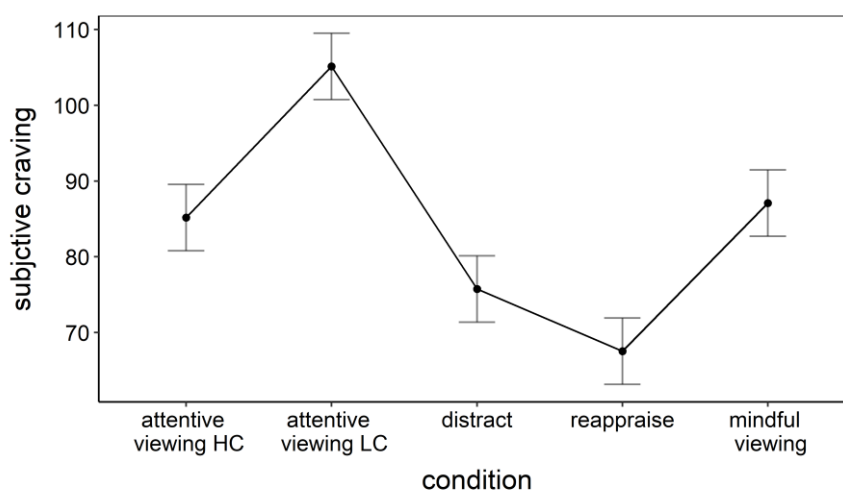
In sum, power in the theta frequency band reflects cognitive effort and can be considered a correlate of SC.

Association between beta and theta activity.

We found the positive correlation between beta and theta activity in resting state ($r=0.42$, $p<0.01$). Based on visual inspection, **Figure 4** and **Figure 5** suggest there might be an inverse relationship between beta and theta. However, we found no significant association when we conducted correlations between each participant's beta and theta ERSPs in different conditions ($r=-0.03$, $p=0.67$; n=190; 38 participants in 5 conditions).

Subjective craving.

LMER analysis with subjective craving as dependent variable revealed that reappraisal and distraction lowered subjective craving compared to attentive viewing HC condition ($p<0.001$). Mindful viewing, on the other hand, did not have statistically significant effect on subjective craving (cf. attentive viewing HC). The effect of calorie content was detected at trend level ($p=0.07$), but the apparent direction of it was reverse to our expectations. That is, the participants reported at trend level significance that they would like to eat, on average, larger amount of LC than HC food immediately after viewing it in the picture. The mean subjective craving rating averages by condition are visualized in **Figure 6**. The LMER model explained (Ω_0^2) 55% of subjective craving ratings' variance. ICC-s showed that subject as random factor explained 34% and picture content as random factor 18% of subjective craving ratings' variance.

Figure 6. Mean subjective craving in different conditions. Error bars depict Least Significant Difference. Mean outside the range is significant.

Individual Differences in Uncontrolled Eating

The descriptive statistics of the analyzed variables are summarized in **Table 3**.

Table 3.
Descriptive statistics of study variables.

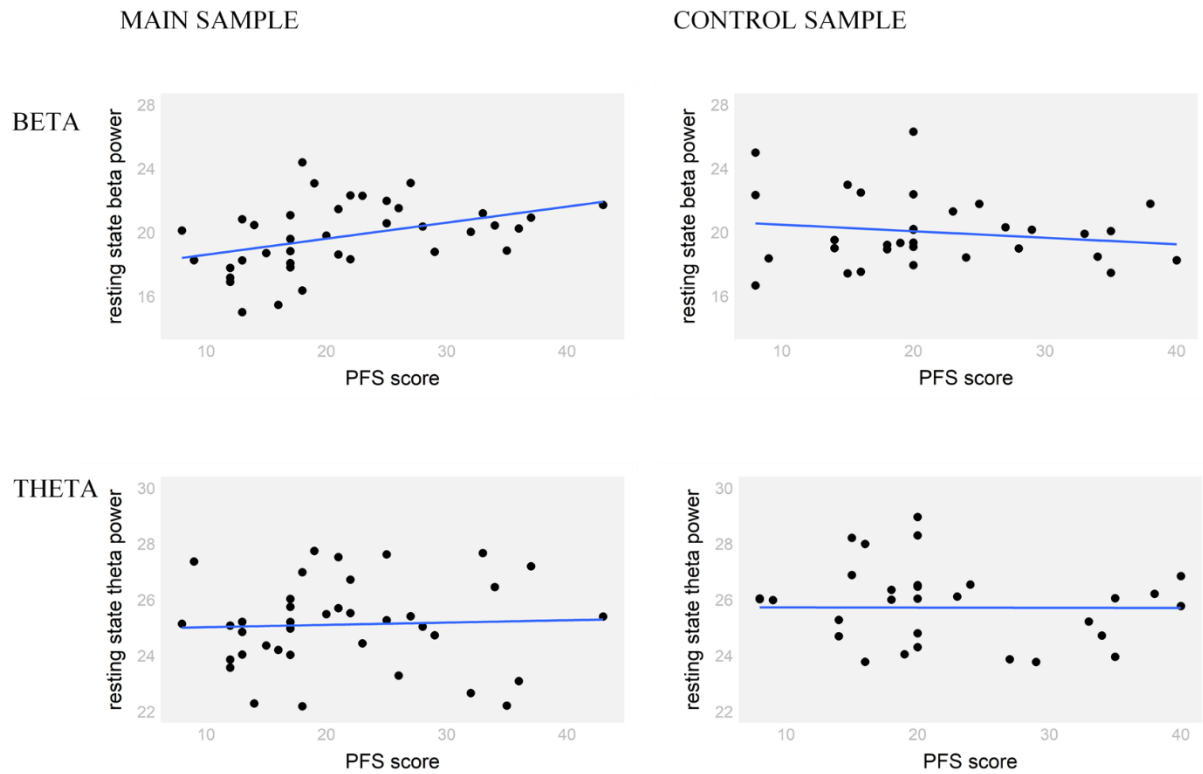|	Main sample				Control sample			
	M	*SD*	*Min*	*Max*	*M*	*SD*	*Min*	*Max*
PFS	21.47	8.64	8	43	22.09	9.28	8	40
Resting state beta	19.76	2.14	15.01	24.39	19.97	2.17	15.01	26.30
Resting state theta	25.11	1.57	22.19	27.75	25.45	1.81	20.48	30.99
Beta ERSP*	-1.05	0.67	-3.16	-0.05				
Theta ERSP*	0.32	0.30	-0.65	0.89				
Subjective craving*	84.22	37.71	6.23	162.10				

Notes: *Averaged across all experimental conditions.

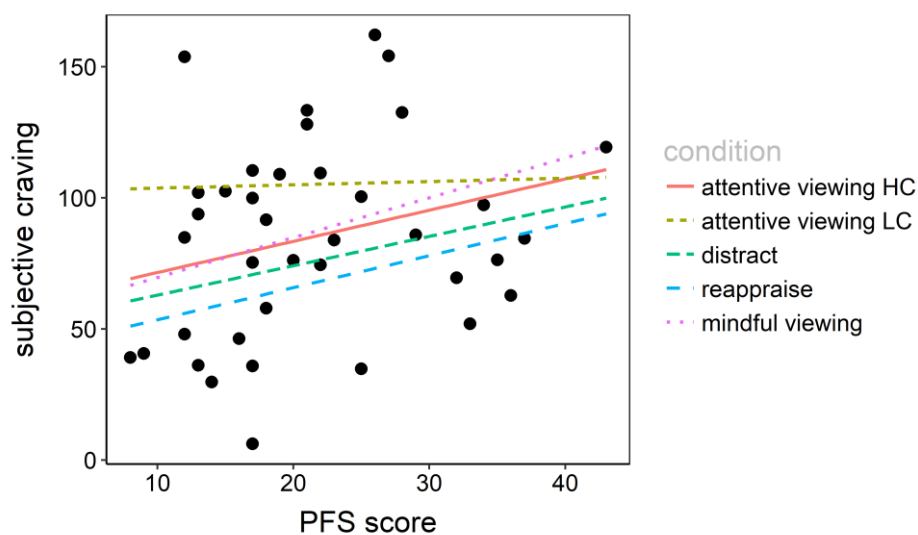### Modulating effects of hunger and food experiment context.

We found that uncontrolled eating, measured by PFS, was significantly positively correlated with resting state beta power ($r=0.4$, $p<0.01$). However, we did not find a significant correlation between PFS and resting state beta in control sample ($r=-0.17$, $p=0.33$). Resting state theta power, on the other hand, was not significantly correlated with PFS neither in our experiment ($r=0.05$, $p=0.79$), nor in control sample ($r=0.0$, $p=0.99$). The results of correlational analyses are visualized in **Figure 7**.

Modulating effect of calorie content.

To better understand the interaction between PFS and experimental condition in LMER analysis of subjective food craving, we graphed a scatterplot with regression lines by condition. **Figure 8** demonstrates that in attentive viewing HC condition as well as in all three regulation conditions (i.e., in these conditions where participants were shown pictures of HC food items) there is a significant positive association between PFS and subjective craving. The slopes of all 4 regression lines are similar and indicate that the higher the PFS score, the stronger the reported craving. The latter does not hold, however, for attentive viewing LC condition. That is, the trait UE does not relate to the subjective craving experienced while viewing pictures depicting healthy food items lower in calorie density.

MAIN SAMPLE   CONTROL SAMPLE

BETA

THETA

Figure 7. Scatterplots illustrating association between PFS and resting state beta/theta in the main sample and control sample.

Figure 8. Scatterplot and regression lines for mean subjective craving and PFS interaction in experimental conditions. Y-axis depicts subjective craving as circle radius (in pixels).

Discussion

The aim of this study was to use EEG beta and theta frequency dynamics to better understand the construct of uncontrolled eating (UE). Specifically, we intended to explore and differentiate whether and to what extent reward sensitivity (RS) and self-control (SC) contribute to UE. Although the interaction between bottom-up and top-down processes in UE is widely accepted, distinguishing these two underlying mechanisms by the means of self-report eating-trait questionnaires has proven to be somewhat difficult (Vainik et al., 2015). Therefore, we designed a study where we recorded the EEG of healthy food-deprived women during resting state and during experimental manipulations when participants first attentively viewed pictures depicting appetizing high-calorie (HC) and low-calorie (LC) food items, and later implemented three common cognitive regulation strategies – reappraisal, distraction, and mindful viewing – to modulate food craving induced by HC food pictures. The subjects also provided us with subjective craving ratings about the hypothetical amount of food they would like to eat, immediately after viewing it in the picture.

Beta as Nonspecific Reward Sensitivity Correlate

Despite the evidence for treating beta as RS correlate being limited, our control analyses provided us with convincing proof that beta indeed captures RS. We found that beta activity was stronger in unregulated viewing of palatable food pictures and the elevation was reduced by implementing regulation. Moreover, beta power significantly predicted subjective craving. However, we did not find the expected difference in beta activity while participants attentively viewed HC compared to LC food pictures. This is contrary to calorie contrast effect that has been previously reported in ERP (Toepel et al., 2009) and fMRI (Killgore et al., 2003) studies and has been interpreted to reflect the higher incentive salience of calorie dense food detected by fast attentional processes. This finding makes the novel suggestion that beta activity is not sensitive to the calorie content of food items but to overall subjective palatability of food, which did not differ between LC and HC stimuli in this study. Hence, beta activity may be associated with a more general, consciously attributed reward value. Non-specific food reward response has been documented in fMRI study by Killgore and colleagues (2003). To our knowledge, we are the first authors to suggest that beta spectral activity might be corresponding EEG correlate.

Reward Sensitivity in Uncontrolled Eating

We found that the beta power was positively associated with UE in resting state, indicating that RS elevation is significantly stronger for these women who, according to PFS, have more problems with non-clinical severity UE. The association between higher UE and stronger RS response was not present in control sample. The expected association as such found in resting state indicates that the context of food experiment and state hunger are important in revealing UE-related vulnerability in healthy women. Later, when we showed the participants stimuli pictures depicting palatable HC foods, we did not detect remarkable enhancement in the correlation between PFS and the beta response in addition to that occurring already in the restful state. Thus, it can be interpreted that the direct exposure to appetizing food stimuli is, in fact, not necessarily required to activate nor augment RS when relevant contextual and state influences are present. These findings are in accordance with the capability approach (Coan et al., 2006) emphasizing that individual differences can be captured when trait-relevant situation and state variables actively engage the underlying biological systems.

Our results are also in line with Tammela et al. (2010) who reported the elevated beta activity in binge-eating subjects in resting state EEG as well as during the exposure to the palatable freshly cooked meal (food experiment context). Moreover, they found that increased beta activity correlated positively with disinhibition factor of eating-trait self-report questionnaire. Similarly, Hume and colleagues (2015) reported the increased beta response during the food task in overweight compared to normal weight participants and interpreted it to reflect the heightened RS response.

Additionally, an analysis of subjective craving responses revealed that women with higher UE reported that they would like to consume more palatable food. Importantly, this association held only when they were shown pictures depicting HC foods. There was no significant association between UE and subjective craving when participants attended to LC food items, although all foods were equally palatable.

To sum up, as we were interested in whether we can reveal any differences in electrophysiological responding between healthy women with higher and lower UE, we found that the difference lies in RS reaction. Self-report craving reported during the experiment also discriminated between women with higher and lower UE but the difference was evident only when calorie dense food was displayed.

Theta as Self-Control Correlate

Our control analyses supported the association between theta and SC. We found that theta activity was significantly stronger when participants implemented regulation tasks compared to attentively viewing HC food pictures. Theta increase was largest in the distraction condition during which attention and working memory were likely most strongly employed.

Increased spectral theta power has been consistently found to reflect cognitive effort in prior research. For instance, Ertl et al. (2013) demonstrated that exerting cognitive reappraisal to modulate response to aversive pictures was correlated with an increase in theta activity at prefrontal region. Further, increased theta activity was positively correlated with the participant-reported success to decrease their emotional response. Nigbur et al. (2011) reported similar results, concluding that theta power enhancement is associated to implementing cognitive control. For review, see Cavanagh & Frank (2014).

Self-Control in Uncontrolled Eating

According to the common neurobehavioral framework, it is the dynamic dual process interaction between RS and SC that largely determines the food intake in modern societies In line with this perspective, we expected to find that subjects with higher UE (i.e., higher PFS score) also demonstrate generally weaker SC in our experiment, indexed by overall weaker theta activity. Alternatively, it was possible that SC problems manifest when women with higher UE cannot lower RS response as effectively as women with lower UE. Neither of these predictions was confirmed according to the results of our analyses. In fact, we did not find any significant association between UE and theta as SC correlate neither in resting state nor during the experiment. Our results also indicate that when healthy women are instructed to use specific cognitive tasks to regulate food craving, the trait UE level does not interfere with the regulation success, at least in the short-term perspective.

Thus, we conclude that, compared to RS, SC-related individual differences do not manifest in women of non-clinical UE while they are being hungry, faced with palatable food stimuli or exerting regulation.

Implications

The results of the present study provided several valuable insights about UE that we regard important to consider in experimental studies. We also deem these to be informative for clinicians.

During the last decade, researchers have been increasingly emphasizing the importance of investigating clinically relevant brain mechanisms underlying problem behaviors and psychological conditions as well as vulnerability factors leading to distinct disorders (Patrick & Hajcak, 2016). Through improved understanding of these mechanisms it would be possible to develop better prevention and intervention strategies. More studies addressing the neurobehavioral mechanisms of UE and regulation are undoubtedly needed (Lowe, van Steenburgh, et al., 2009). It is important to first understand how food reward is processed normally in the brain, which in turn makes it possible to recognize pathology and judge which of the possibilities best apply to a specific eating problem (Berridge, 2009). Thus, RS and SC brain correlates in combination with self-report measures might aid in identifying individuals who are at risk for developing disinhibited eating and binge eating disorder. This knowledge, in turn, could be of vital importance in developing new cognitive-behavioral interventions for binge eaters (with the aim of coping with food cravings, regulating urges and behavior to maintain health), in evaluating their efficacy and measuring treatment outcome.

We emphasize the relevance of capability approach (Coan et al., 2006) when experimentally investigating UE using EEG correlates. That is, the appropriate state and situational aspects need to be carefully considered. We found that the influence of state hunger is important in revealing the relationship between UE and RS. In addition, hunger probably acts together with situational influences (i.e., the context of participation in a food-related experiment, in case of this study). As discussed already earlier, we did not find that RS activation necessarily requires the exposure of food stimuli or attempt to regulate the craving. Instead, we demonstrated that RS activates in rather ambivalent circumstances such as modeled by the resting state period in our experiment. Concerning stimuli selection, the calorie content and subjective palatability of depicted food needs to be considered. We demonstrated that calorie density aspect was important in revealing the relationship between UE and subjective craving during the experiment but did not change the association between UE and beta as RS correlate. These findings highlight the importance of measuring, analyzing, and interpreting both resting state and experimental recordings as well as subjective self-report measures in parallel with brain correlates in the framework of capability approach of individual differences.

Since UE is a dimensional construct, we emphasize that it is important to choose the questionnaire that matches the sample and enables to capture the UE of suitable severity on the continuum (Vainik et al., 2015). Since we conducted our study in non-clinical sample, that

is with women who did not meet the criteria for eating disorder diagnosis, the PFS (Lowe, Butryn, et al., 2009) was appropriate for us to use. PFS is also adequately validated and frequently used questionnaire that enables to make comparisons with other studies.

Limitations and Future Directions

Since the use of beta and theta frequency dynamics as RS and SC correlates to investigate UE is a novel approach, the reported findings are still of preliminary nature. There are several limitations that need to be taken into consideration.

Traditionally, beta activity has been associated with sensorimotor functions (Pfurtscheller, Stancák Jr., & Neuper, 1996). However, we regard it unlikely that beta activity measured in our experiment reflects movement-related activity. First, we found the association between PFS and beta in resting state, where participants sat still and did not have to exert any task that required movements. Second, during the experiment the participants reported subjective craving randomly only after one out of three presentations of each picture. Thus, the possibility that beta reflects preparatory motor activity related processes is also improbable. Thirdly, these periods when participants gave the answers by clicking computer mouse are not included in the EEG recordings we analyzed.

The limitation of EEG as a method concerns the lack of precision in associating distinct spectral activity with specific neural substrates. Thus, we regard it out of scope of the present study. The neural generators might be identified by brain imaging methods.

Although our sample size is reasonably large for an EEG study, the number of participants is still small for investigating individual differences. Furthermore, our inferences are restricted to non-eating-disordered individuals. We suggest replicating the findings with larger number of participants and including men as well as clinical samples (i.e., individuals with recurrent uncontrolled eating episodes and binge eating disorder patients). It might be that the manifestation of remarkable SC problems indicates the transition from subclinical UE symptoms to clinical range of UE problems and eating disorders.

Concerning stimuli, the differences in the actual calorie content between HC and LC food displayed in pictures were not controlled, which makes it hard to draw definite conclusions about the effect of calorie content or its' absence *per se*. The measure we used for acquiring subjective craving ratings might be optimally informative in future studies when the calorie content of food items depicted in stimulus pictures is estimated and controlled more

objectively. This is because the amount of food participants report to desire probably depends on calorie density. Further, the palatability and healthiness of the stimulus pictures used in the experiment had been previously rated by independent sample. In future studies, the participants might provide the ratings after the experiment as well. What is more, all participants were presented with the same food pictures, although there are considerable individual differences in food preference and food cravings are of idiosyncratic nature. To better account for these individual differences, the participants in future studies might be allowed to determine which of the food items from larger pool of food categories trigger strong craving for them personally. There are, in fact, researchers who have used idiosyncratic stimuli in their experiments (e.g., Giuliani et al., 2013; Smeets et al., 2009). Another promising approach to strengthen the motivational relevance is to manipulate the availability of actual food in the experimental settings (e.g., real consumption during or in the end of the experimental procedure), which would increase both the RS and SC (e.g., Blechert et al., 2010; Werthmann et al., 2013).

Finally, investigating the exertion of SC strategies in experimental settings is different from coping in real life situations. In laboratory, participants are carefully instructed to implement specific regulation tasks. In everyday situations, it is probably remarkably more complicated, because first it is necessary to recognize the need to regulate and then to be able to find the best strategy for implementing depending on specific context (Sheppes, Suri, & Gross, 2015). Therefore, we conclude that all interpretations of regulation effects are also restricted to short-term experimental context. Future studies should seek to conduct experimental studies that enable to explore and draw stronger inferences about coping in real life situations.

Conclusions

This study demonstrates the feasibility of using EEG beta and theta frequency dynamics to provide insights into reward sensitivity and self-control mechanisms underlying uncontrolled eating. We found that uncontrolled eating in healthy female participants correlated with beta activity which is associated with bottom-up reward sensitivity, but not with theta activity which relates to self-control processes. This difference occurred during the resting state measurement prior to the experiment rather than in response to stimuli or regulation. We interpreted this pattern to mean that participants who are more susceptible to the influences of appetizing food exhibit significantly stronger reward sensitivity activation in a broadly food-relevant context. This suggests that direct exposure to food stimuli is, in fact, not necessarily required to activate nor to significantly amplify reward sensitivity response. Further, when

given specific regulation tasks to implement, the higher degree of non-clinical range uncontrolled eating does not seem to interfere the regulation success. By contrast, physiological hunger may be an influential factor contributing to the activation of reward sensitivity. Taken together, these findings offer several important implications for understanding uncontrolled eating, for conducting future studies, and are also informative for clinicians.

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