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**AUTOMATIC PROCESSING OF VISUAL FOOD STIMULI DURING HUNGER: A
VISUAL MISMATCH RESPONSE STUDY**

Master's thesis

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Running head: Automatic processing of food stimuli during hunger

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ABSTRACT

The aim of this thesis was to investigate whether the presentation of visual food stimuli elicits visual mismatch negativity (vMMN) in an oddball paradigm and whether the amplitude of the vMMN is modulated by hunger. For this purpose, 18 right-handed women underwent two experimental sessions: hunger and fed conditions. Participants were instructed to complete a 2-back working memory task while stimuli depicting high fat savoury (HFSA) and high fat sweet (HFSW) foods were presented as deviants in a stream of neutral standard stimuli in the periphery of the screen. To examine whether the effect of hunger was food-specific, neutral deviants were used as control stimuli. Further, emotional blink of attention (EBA) was used to validate the vMMN. Deviant minus standard difference waveforms yielded significant mismatch responses in the early, mid-latency, and late time windows. In HFSA, the modulation of hunger was evident in the early and mid-latency time windows pertaining to automatic stimulus detection. In HFSW, the modulation of hunger was not observed. In addition to the food deviants, hunger also modulated the responses to the neutral stimulus. Therefore, the modulation of hunger pertaining to general information processing cannot be ruled out. As the EBA task did not yield anticipated results, the mismatch response paradigm could not be validated via EBA. In conclusion, vMMN might prove to be a reliable measure in investigating automatic food-cue processing after additional attempts at vMMN validation with different food stimuli have been made.

Keywords: automatic stimulus processing, hunger, food, vMMN

Visuaalsete toidustiimulite automaatne töötlus nälja korral: lahknevusvastuse uuring

LÜHIKOKKUVÕTE

Käesoleva magistritöö eesmärk oli uurida, kas visuaalsed toidustiimulid kutsuvad esile visuaalse lahknevusnegatiivsuse (vMMN) *oddball* katseparadigmas ning kuidas erineb see nälja- ja kontrolltingimuse võrdluses. Katses osales 18 paremakäelist naist, kes läbisid kaks katsetingimust: nälg ja kontrolltingimus. Katseisikutel paluti ekraani keskel lahendada 2-tagasi töömälu ülesannet, näidates samaaegselt ekraani neljas perifeerses nurgas deviantidena kõrge rasva sisaldusega magusaid (HFSW) ja soolaseid (HFSA) toidupilte lisaks tihti ilmnevale neutraalsele standardile. Veendumaks, et ilmenud vMMN on toiduspetsiifiline, kaasati mõlemasse blokki üks neutraalne deviantstiimul. Lisaks läbisid katseisikud vMMN valideerimiseks emotsionaalse tähelepanu silmapilgutuse (EBA) katseparadigma. Deviant miinus standard lahknevuskõveraid uurides ilmnis, et olulised lahknevusvastused ilmnisid varajases, keskmises ja hilises ajaaknas. HFSA bloki puhul ilmnis nälja mõju automaatse töötluksuga seotud varajases ja keskmises ajaaknas. HFSW puhul nälg stiimuli töötlust aga ei mõjutanud. Lisaks toidustiimulitele mõjutas nälg ka neutraalse stiimuli töötlust. Seega ei saa välistada võimalust, et nälg võib mõjutada ka üldist informatsioonitöötlust. Kuna EBA katseparadigma abil ei saavutatud oodatud tulemusi, ei olnud võimalik selle abil vMMNi valideerida. Kokkuvõttes võib vMMN pärast täiendavat valideerimist erinevate toidustiimulitega osutada usaldusväärseks meetodiks toidustiimulite automaatse töötluks uurimisel.

Märksõnad: automaatne stiimulitöötlus, nälg, toit, vMMN

INTRODUCTION

Food as a highly salient stimulus category

Due to its relevance for survival and its inherently rewarding and hedonic nature, food is a highly salient biological stimulus category (Toepel, Knebel, Hudry, le Coutre, & Murray, 2009). From an evolutionary viewpoint, it would be therefore crucial for the cognitive system to be able to automatically orient towards food-related cues in the environment (Nummenmaa, Hietanen, Calvo, & Hyönä, 2011). Nevertheless, in today's obesogenic environment where people are constantly bombarded with high calorie delicious foods, this sensitivity to food cues could lead to obesity, eating disorders, and various eating-style related conditions. In fact, several behavioural as well as neuroimaging methods indicate that overweight and obese populations (Castellanos et al., 2009; Nijs, Franken, & Muris, 2010; Stockburger, Weike, Hamm, & Schupp, 2008), women with eating disorders, and external and emotional eaters (Wolz, Fagundo, Treasure, & Fernández-Aranda, 2015) differ in terms of food cue reactivity. Further, these differences in food cue processing have also been shown to exist in the early processing stages pertaining to automatic orienting to salient stimuli (Wolz et al., 2015). Therefore, as to devise better diagnostic and intervention methods, it would be crucial to find underlying brain mechanisms pertaining to early food cue reactivity and the differences among individuals.

Hunger on food cue processing

One way how to investigate food cue reactivity could be done by manipulating food reward or incentive salience of food. According to the model put forward by Berridge (1996), two separate systems termed 'wanting' and 'liking' contribute to food reward. Food reward refers to the momentary value of food to the individual at the time of ingestion (Rogers & Hardman, 2015) and is therefore indicative of food intake and preference (Berridge, 1996). Liking is associated with the sensory pleasure or palatability of food and is subserved by opioid and GABA/benzodiazepine systems, whereas wanting is associated with appetite/incentive motivation and is mediated by the mesolimbic dopamine system. As the incentive salience of food and thus, subsequent food intake, is heavily influenced by physiological states associated with energy balance (i.e., hunger), it has been proposed that hunger amplifies food reward by

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modulating the wanting system (Rogers & Hardman, 2015). Hence, influencing hunger levels provides a way to manipulate food reward.

As attentional mechanisms prioritize the processing of highly salient and unexpected stimuli in the environment at the expense of other ongoing information processing (Corbetta & Schulman, 2002), it would be logical to assume that such motivational state as hunger would bias attention to detect food-related stimuli in the environment. This hypothesis has indeed been confirmed by a several behavioural studies (Castellanos et al., 2009; Dobson & Dozois, 2004; Placanica, Faunce, & Soames Job, 2002). For instance, Piech, Pastorino, & Zald (2010) used the emotional blink of attention (EBA) paradigm (Most, Chun, Widders, & Zald, 2005) to investigate whether hunger modulates the attentional capture of highly salient food stimuli relative to neutral and non-food (romantic) emotional stimuli. In an EBA paradigm, distractor stimulus is interspersed in a stream of rapidly displayed neutral images, and the participant is instructed to detect a target following the distractor. As emotional stimuli allocate more attentional resources, they might impair the detection of following targets. Piech et al. (2010) found that food stimuli impaired target detection in comparison to neutral and romantic stimuli during hunger, whereas no such effect was observed in the satiated state. Further, the attentional blink was observed when target stimulus appeared two presentations (200 ms) after the distracting food image. Thus, hunger biased attention towards food stimuli.

Event-related potentials – a measure of attentional processing

In addition to behavioural measures, automatic attention could be investigated with electroencephalography (EEG). EEG, a noninvasive measurement of neural activity that can be recorded from multiple scalp regions (Birbaumer et al., 1990), is a neuroimaging method that has superior temporal resolution. Therefore, the use of event-related potentials (ERPs) that are tied to specific cognitive events and reflect positive and negative deflections in the ERP waveform, is an excellent method to study the temporal course of attention-related processes regarding stimulus presentation. Specifically, ERPs allow researchers to investigate the early, mid-latency, and late components of affective processing (Meule, Kübler, & Blechert, 2013).

Although early ERPs (< 300 ms) were previously considered to reflect the processing of sensory features, electrocortical research nowadays has pointed out that early processing of early (e.g., N100, 100-200 ms) and mid-latency (e.g., early posterior negativity [EPN], 200-300ms) ERPs

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components could index selective attention instead (Olofsson et al., 2008). Further, a considerable amount of research points towards the fact that early ERPs could also be modulated by emotional or motivational content of stimuli (e.g., Schupp, Flaisch, Stockburger, & Junghüfer, 2006), as aforementioned components also direct attentional processes. For example, Uusberg et al. (2013) found that the activity of EPN was modulated by the emotional content of the stimulus regardless of whether the stimulus was task-related or not, indicating an automatic discrimination between emotional and neutral stimuli. Therefore, early ERPs occurring before 300 ms after stimulus presentation could be associated with automatic orientation towards salient stimuli. Long-latency ERPs (>300 ms; e.g., P300), on the other hand, are associated with sustained and motivated attention, memory storage, and are subject to cognitive modulations (Schupp et al., 2006).

A large number of electrophysiological studies on food cue processing have also incorporated hunger manipulation in order to study attentional processes related to early and late processing of affective food stimuli. Most prominent results so far have been found in the late processing stages of stimulus evaluation such as P300 reflecting conscious attention allocation and motivated attention (Schupp et al., 2006). For example, Nijs, Muris, Euser, & Franken (2010) found that in normal-weight women, hunger and satiety were associated with an attentional bias to food images relative to neutral images, as indicated by an increased P300 amplitude in posterior sites in comparison to neutral images. Further, the P300 amplitudes were enlarged for food images during hunger in comparison to satiety, and were correlated with subjective hunger, and subsequent food intake in the bogus task. Stockburger et al. (2009) also found that 24-hour food deprivation was associated with an increased amplitude of the occipito-temporal negativity and centro-parietal positivity at 300-360 ms after stimulus presentation. Additionally, hunger also increased the amplitudes of the Late Positive Potentials (LPPs) in a later time window (~450-600 ms). These results point towards the fact that salient food stimuli are differently processed in the brain in comparison to neutral objects, and this different processing is further enhanced by hunger.

Even though many studies pertaining to food viewing have demonstrated that food images elicit sustained attention, some studies using EEG have also shown that the presentation of food images also evokes automatic orientation towards them. Toepel et al. (2009) found that the brain automatically tracks the energetic value and reward-related properties of food, as indicated by different ERPs to high and low fat food images occurring as early in the processing

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stream as 165 ms. Specifically, the activation was observed in occipital and temporo-parietal regions, suggesting an important role for the visual cortex in determining the salience of the stimulus. On the other hand, Nijs, Franken, & Muris (2010) found indications of automatic attention to food stimuli in only obese participants, as food words in a modified Stroop task were related to an enlarged P2 component in central electrodes. No such effect was found in normal-weight participants. More consistent results regarding early processing of food stimuli have also been found in relation to food deprivation. Stockburger et al., (2008) showed that food deprivation in men enhanced ERPs to food images in comparison to neutral and emotional non-food images. Specifically, enlarged amplitudes over occipito-temporo-parietal regions around 170-310 ms were found relative to other pictures, pointing towards enhanced visual attention to food stimuli only. Similarly, Stockburger et al. (2009) found that food images presented during hunger were associated with an increased positivity over posterior sites that developed around 70 ms and lasted until 300 ms. In sum, these results indicate that increased automatic attention by enhancing visual attention to food cues is also modulated by hunger.

Visual mismatch negativity

In addition to the traditional ERP approach, automatic attention could be studied with the use of mismatch negativity (MMN; Näätänen et al., 1978). MMN is a component of the event-related potential that is elicited by presenting infrequent deviant stimuli in an array of frequent standard stimuli during sensory processing (Näätänen, Paavilainen, Rinne, & Alho, 2007). Specifically, MMN is calculated by subtracting the averaged ERP for the frequent standard stimulus from the averaged ERP for the infrequent deviant stimulus. In addition to mismatch negativity responses, a few vMMN studies have also reported mismatch positivity responses in later latencies (e.g., Kreegipuu et al., 2013; Stefanics et al., 2012). So far MMN has been extensively studied in the auditory domain and is considered to reflect any discriminable change in the auditory processing – an error, danger, or a need to react (Näätänen et al., 2007).

As MMN is also observed in other modalities, such as vision (e.g. Kecskés-Kovács, Sulykos, & Czigler, 2013; Kreegipuu et al., 2013; Larsen, van Strien, Eisinga, & Engels, 2006; Li, Lu, Sun, Gao, & Zhao, 2012; Pazo-Alvarez, Cadaveira, & Amenedo, 2003), it could be argued that MMN is not only specific to the auditory domain. Visual mismatch negativity (vMMN) is analogous to the auditory MMN, and has mostly been witnessed in the occipital area (Stefanics et al., 2012). In addition to detecting changes in the physical features of the stimuli (Pazo-

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Alvarez et al., 2003), more complex stimuli that incorporate higher-order abstract features requiring cognitive and affective processing have also been shown to elicit vMMN. For instance, emotional facial expressions have been repeatedly shown to elicit vMMN. For example, Li, Lu, Sun, Gao & Zhao (2012) demonstrated that sad faces as deviants elicited vMMN in an oddball paradigm as well as in an equiprobable control block at occipital-temporal regions. Similarly, Stefanics et al. (2012) used photos of happy and fearful facial to study the processing of unattended facial stimuli. As MMN is best observed when the participant does not attend to the MMN-eliciting stimuli, stimuli depicting facial expressions were presented in the periphery, whereas participants had to perform a visual detection task in the center of the visual field. They found that both fearful and happy faces elicited vMMN in 150-220 ms and 250-360 ms intervals over bilateral occipito-temporal sites. Likewise, vMMN has been shown to be sensitive to gender category (Kecskés-Kovács et al., 2013), and even untrustworthiness of the face (Kovács-Bálint, Stefanics, Trunk, & Hernádi, 2014). Hence, vMMN seems to be a reliable paradigm to be used in the automatic attention and affective processing domain.

Utility of the vMMN in food cue reactivity research

There are several implications for the use of the vMMN paradigm in food cue reactivity research. First, vMMN could be evoked irrespective of the participant's attention. In fact, often such tasks that aim to direct attention away from the MMN-eliciting task are used to prevent the confounding effects of attention-dependent ERP components (Näätänen et al., 2007). The possibility to evoke vMMN in the absence of attention is especially important in studying clinical groups (Näätänen, 2000), such as eating disorder patients. Secondly, when calculating vMMN difference waveforms, individual differences are taken into account. Specifically, individual difference waveforms are calculated instead of averaging across participants. In addition, several control blocks (e.g., equiprobable design, stimuli presented as both deviants and standards in different blocks) have been designed and utilized by several vMMN researchers (e.g., Kovács-Bálint et al., 2014; Qian et al., 2014) in order to demonstrate that elicited vMMN truly reflects selective processing of a stimulus due to its salient properties. Thus, MMN proves to be a valid measure of automatic attention.

Purpose of the thesis

The aim of the current study is to investigate the automatic processing of visual food stimuli. First, we aim to test whether the automatic detection of salient food stimuli is evidenced by using the vMMN paradigm. As individuals also differ in their satiety responsiveness and some individuals are prone to eat in the absence of hunger (French et al., 2012), we also included the fed condition in our analyses. Secondly, we aim to investigate whether the automatic processing of food stimuli is modulated by hunger. Thus, we expect that during hunger the automatic processing of food stimuli is amplified. As visual MMN has mostly been found in the occipital area (Stefanics et al., 2012), we will also focus on the occipital electrodes. Further, we aim to validate the vMMN paradigm by comparing the results with the EBA task. We use the EBA task for validation for several reasons. First, the modulation of hunger on attentional capture by food stimuli at lag 2 (200 ms after stimulus presentation) has been recently demonstrated by Piech et al. (2010). Secondly, Berti (2011) demonstrated that the attentional blink at lag 3 (300 ms) was evoked together with an occipital negativity. Thus, both vMMN and attentional blink are shown to measure automatic attention.

Based on the literature, three hypotheses were postulated:

- 1) Presenting visual food stimuli as deviants elicits vMMN in the occipital area in an oddball paradigm during hunger and fed conditions.
- 2) The amplitude of the vMMN elicited by food stimuli in the occipital area is larger during hunger in comparison to fed condition.
- 3) The amplitude of the vMMN in the occipital area and the percentage of correct trials in EBA at lag 2 (200 ms after the distractor stimulus) are positively correlated during hunger and fed conditions.

METHOD

Participants

Participants were recruited via various mailing lists and social media. The initial sample consisted of 25 right-handed women. 3 women were eliminated from the sample due to poor data quality, and 3 women excluded from the final analysis, as they only attended the experiment once. Therefore, the final sample consisted of 18 right-handed women aged 20-47 ($M = 25.2$, $SD = 7.35$ yrs) with the mean body-mass index (BMI) of 23.35 ($SD = 4.3$). Participants had normal or corrected to normal vision. Before enrolling in the experiment, participants had to fill in a questionnaire to evaluate eligibility for the study. Only women were invited to participate as gender differences regarding food cue reactivity have been reported in the literature (e.g., Wang et al., 2009). Exclusion criteria included a diagnosis of current psychiatric illness (e.g., eating disorder) or medical condition (e.g., diabetes). Participants who were pregnant, breastfeeding, or were diagnosed with a neurological condition (e.g., epilepsy, migraine) were also excluded from the study. Psychology students were offered course credit for their participation. The data was collected from October 2016 until March 2017 and the study was approved by the Research Ethics Committee of the University of Tartu.

Self-report measures

Eating Disorders Assessment Scale (EDAS; Akkermann, 2010) is a 29-item self-report questionnaire that measures eating disorder symptoms characteristic of anorexia nervosa (AN), bulimia nervosa (BN), and binge eating disorder (BED). The participant has to indicate on a six-point Likert-type scale ranging from 0 (never) to 5 (always) the extent to which the item describes her eating behaviour during the last three months. The scale consists of 4 subscales: Restrained eating, Binge eating, Purging, and Preoccupation with body image and body weight.

Stimuli

In order to choose the most suitable stimuli for the EEG experiment (described in detail below), 16 food images depicting high fat savoury (HFSA), high fat sweet (HFSW), low fat savoury (LFSW), and low fat sweet (LFSA) foods were chosen from the Internet. Further, a neutral object resembling each food image was chosen. For instance, a food image depicting a bar of chocolate was paired with a brown wallet. This resulted in total of 16 neutral objects. The visual parameters regarding image contrast (defined as the mean value of the image pixels associated

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with red, green, and blue components of the image) and luminance (defined as the standard deviation of the mean value of the image pixels associated with red, green, and blue components of the image) were also adjusted to prevent that any stimulus would be processed differently due to its visual distinctiveness.

Next, an online survey was carried out in spring 2016 to evaluate the images. Participants were instructed to rate food images on their appetitiveness, valence, arousal, attention-eliciting qualities, and healthiness on a visual analogue scale (VAS). Neutral objects were also rated on their valence, arousal, and attention-eliciting qualities on VAS. The demographic data regarding the participant's age, education, and gender was also obtained.

The sample consisted of 51 participants (12 males) with the mean age of 37 (SD = 12.60) and the mean BMI of 25.15 (SD = 4.62). Based on the ratings obtained via the survey, stimuli for the HFSA and HFSW blocks were chosen for the EEG experiment. In addition to the images corresponding to one's category (i.e., HFSW or HFSA), images that were visually the most similar were chosen for each block to avoid the confounding effect of visual distinctiveness in the vMMN elicitation. Thus, stimuli for the EEG experiment consisted of four coloured photographs depicting high fat savoury (HFSA) and high fat sweet (HFSW) foods. Neutral stimuli consisted of four coloured photographs of neutral objects (e.g., a clock) that were visually matched with foods. The first (D1) and second deviants (D2) constituted food images, and the third deviant (D3) a neutral image for both HFSA and HFSW. The fourth stimulus within each block constituted the standard stimulus. To examine whether the effect of hunger was food-specific, neutral deviants were used as control stimuli. The stimuli used in the EEG experiment are presented in Figure 1.

As it proved challenging to adjust the stimuli within each block based on their appetitiveness, arousal, valence, and attention-eliciting qualities, the mean level of attention elicitation was defined as the criterion. Even though the stimuli differed in terms of their attention-eliciting qualities [$F(3,150) = 3.04, p = .0309$] in HFSA, there was only a significant difference in the mean level of the attention elicitation between two stimuli [$t(150) = -12.82, p = .0261$]. Thus, D2 elicited less attention than the standard stimulus. In HFSW, the stimuli also differed in terms of attention elicited [$F(3,151) = 5.64, p = .0011$]. Similarly to HFSA, there was a significant difference between two stimuli [$t(151) = 4.79, p = .0004$] with D1 eliciting more attention than D3.

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Stimuli for the emotional blink of attention task (EBA, see below) consisted of coloured photographs depicting high fat savoury (HFSA) and high fat sweet (HFSW) foods, and neutral images of household objects. These three categories constituted distractor stimuli. Target stimuli included various images of clockwise and counterclockwise rotated images of vehicles. Distractor and target stimuli were interspersed in a rapid stream of neutral images depicting vehicles. All stimuli were previously matched according to their contrast and luminance levels, as well as valence and arousal (see Arumäe, 2017, In Prep).

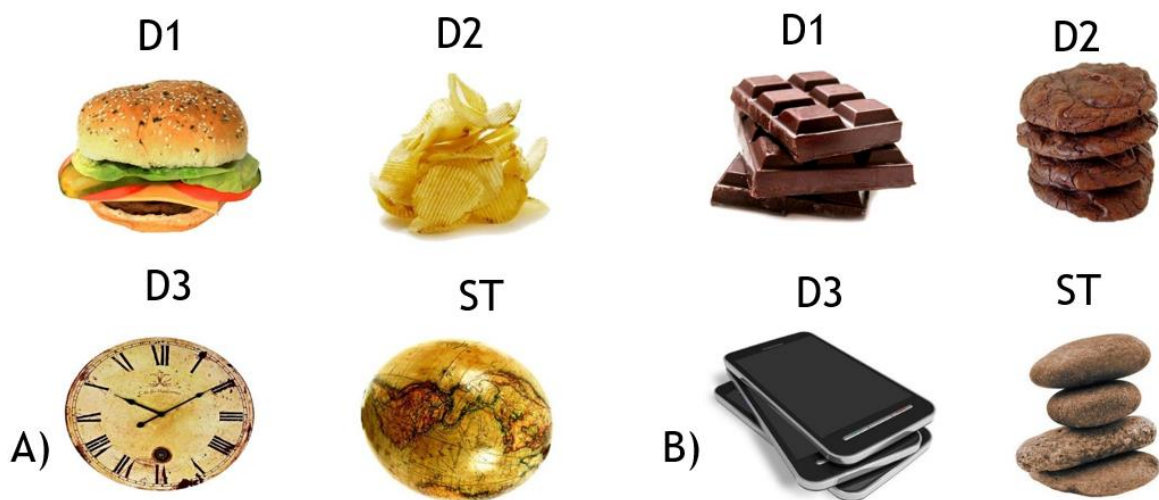


Figure 1. Stimuli used in the EEG experiment. A) Stimuli belonging to the high fat savoury (HFSA) block; B) Stimuli belonging to the high fat sweet (HFSW) block; D1 – first deviant stimulus, D2 – second deviant stimulus, D3 – third deviant stimulus, ST – standard stimulus.

EEG task

The EEG experiment took part in a dim and electrically shielded room. The participant was instructed to sit calmly, avoid excessive blinking, and to follow the instructions presented on the screen. The experiment consisted of four blocks that were presented with using MATLAB (MathWorks, Natick, Massachusetts, United States). The order of the blocks was randomized. Blocks including HFSA and HFSW food images included two food pictures and one neutral picture as deviant stimuli, and one neutral picture as the standard stimulus. Images of HFSA and HFSW were presented in separate blocks in an oddball paradigm, where deviant stimuli ($p = .1$ each) appeared in a dense line of standards ($p = .7$). In total, there were 1000 presentations of stimuli, with each deviant being presented 100 times. The same stimuli in HFSA and HFSW were also presented in an equiprobable paradigm that served as a control block. In an equiprobable design, each stimulus was presented with an equal probability ($p = .25$). In total,

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there were 400 presentations of stimuli, with each stimulus being presented 100 times. The results of the equiprobable design are not discussed in the current thesis.

In the EEG experiment, participants were instructed to complete a 2-back working memory task in the middle of the screen. A list of letters were used as stimuli in the working memory task. Capital letters of B, D, H, K, R, S, and T were used in the 2-back working memory task. The participant was instructed to press the right button of the mouse when the stimulus matched the one that was presented two steps earlier. When the stimulus did not match, the participant was instructed to press the left button of the mouse. At the same time, stimuli presented in oddball or equiprobable paradigms appeared at the upper-left, upper-right, lower-left, and lower-right of the screen. Participants were instructed to ignore the stimuli in the periphery and focus on completing the working memory task. The presentation of the stimuli for the periphery and center was out of sync to avoid concurrent reactions. Thus, stimulus onset time in the periphery was 450 ms with an inter-stimulus interval of 250 ms, stimulus onset time in the center was 1500 ms with an inter-stimulus interval of 500 ms. A graphical depiction of the experimental procedure is presented in Figure 2.

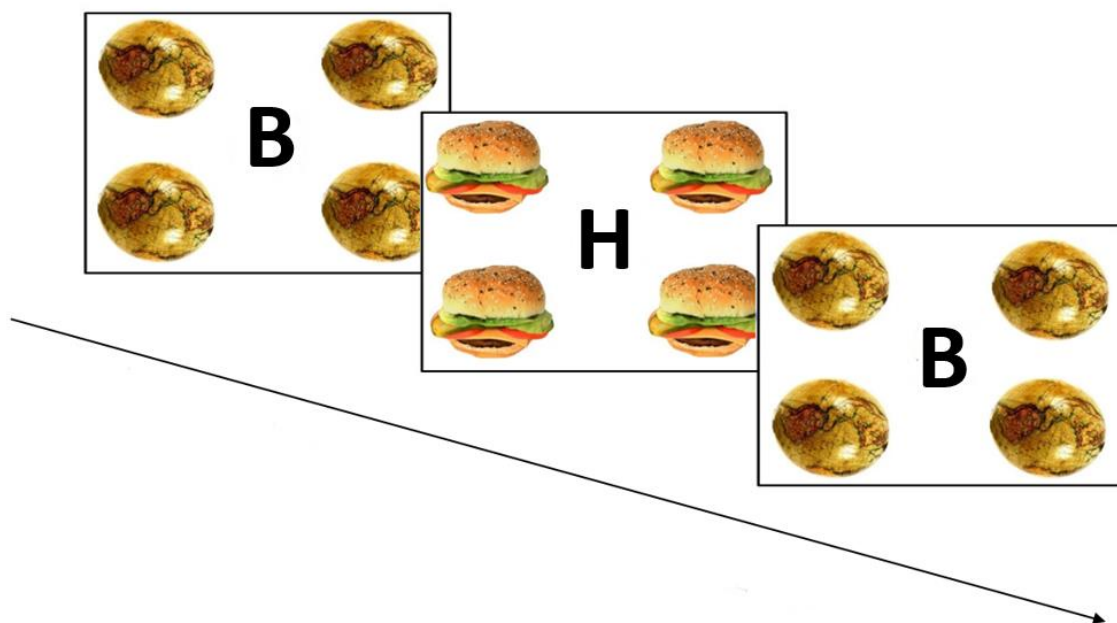


Figure 2. A graphical depiction of the EEG experiment with the stimuli from the HFSA block. Note that the stimulus onset time in the periphery and in the center is out of sync.

Emotional blink of attention

The emotional blink of attention (EBA) task (Piech et al., 2010) consisted of rapid presentations of images embedded with distractor and target stimuli. The participant was instructed to identify the target among each trial, and indicate whether the target was rotated clockwise or counterclockwise. Every trial included a distractor that belonged to one of the three categories – HFSA, HFSW, or neutral. The targets occurred either two (lag 2; 200 ms) or four (lag 4; 400 ms) presentations after the distractors. Also, additional control block was implemented where no distractor stimuli were presented (lag 0). The adaptation of EBA with food stimuli in an Estonian-based sample is also discussed in another thesis (Arumäe, 2017; In Prep).

Procedure

As the study used a within-subjects design, every participant was instructed to attend the experiment twice to undergo two experimental conditions: hunger and fed. The time interval between the two sessions was at least a week and the order of conditions was counterbalanced across participants. Before attending the experiment, participants were instructed to fill in several self-report questionnaires pertaining to their eating disorder related features, personality, impulsivity, and mood. Only the results of EDAS related to eating disorder features are investigated in the current thesis.

Next, participants were instructed to refrain from eating 10-12 h before the start of the experiment, and invited to enter the lab at 9AM without having had breakfast. Upon entering the lab, participants filled in informed consent form, and rated their subjective hunger, fatigue, and current mood on a visual analogue scale (VAS). Next, glucometer Accu-Check Performa Nano was used to measure blood glucose level in order to attain an additional measure of hunger. Participants' mood, subjective hunger, and fatigue were also rated before, in the middle, and at the end of the EEG experiment, and after completing the EBA task. At the beginning and end of the experiment, the critical flicker frequency test (CFF, Simonson & Brozek, 1952) was also administered to measure the wakefulness of the nervous system.

Next, participants were assigned either to a hunger or satiety condition. Participants in the satiety condition were given an instant porridge consisting of approximately of 350 kcal, whereas participants in the hunger condition received breakfast at the end of the experiment.

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The blood glucose level of the participants in the satiety condition was measured for the second time 45 minutes after breakfast. Participants then completed the EEG experiment. Before and after the EEG experiment, resting state (baseline) EEG was measured with open and closed eyes. After the EEG experiment, participants completed the EBA task. After the EBA task, blood glucose level of the participants in the hunger condition was measured and all participants were instructed to rate the stimuli in the EEG experiment based on their appetitiveness, valence, and whether the stimulus grabbed attention. Also, weight, height, and body fat percentage was measured in participants in the hunger condition. The experimental procedures for the hunger and fed conditions are depicted in Figure 3.

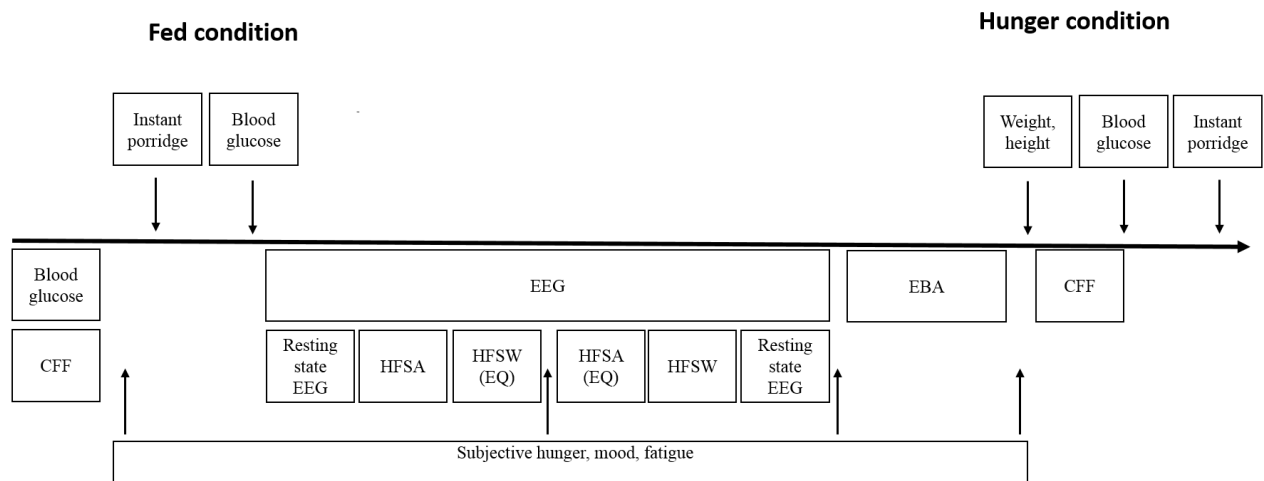


Figure 3. The experimental procedure for the hunger and fed conditions. The procedure depicted below the timeline is the same in both conditions, the procedure depicted above the timeline refers to additional aspects related to the condition. CFF – critical flicker frequency, EBA – emotional blink of attention, HFSA – high fat savoury, HFSW – high fat sweet, EQ – equiprobable design.

EEG measurement

The EEG data were recorded with a 64-channel active electrode kit (Active Two, Biosemi B. V., Amsterdam, The Netherlands). The data were online recorded with 512 Hz and band-pass filtered 0.16 – 100 Hz. The electrodes were placed on the scalp by the international 10-20 system (Jasper, 1958). Additionally, four electrodes were attached to the participants' face to detect eye blinks and eye movements, and two electrodes were placed on earlobes as reference electrodes. The raw EEG data were offline processed in BrainVision Analyzer 2.1 (Brain

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Products GmbH, Munich, Germany). The data were referenced to the linked earlobe electrodes, and names from the 10-20 system were added. The data were filtered with Butterworth Zero Phase filter (24 dB/oct, 0.1 – 30 Hz) and corrected for eyeblinks using the Gratton and Coles algorithm (Gratton, Coles, & Donchin, 1983). Segments starting at -100 until 600 ms after the stimulus presentation were selected for analyses. Baseline correction was made at 100 ms before stimulus onset and segments that were lower or higher in amplitude than $-100 \mu\text{V}$ were removed. Segments that had at least 100 ms of activity that was lower than $0.5 \mu\text{V}$ were also removed. When the maximal allowed absolute difference of two values in the segment exceeded $100 \mu\text{V}$, the segment was also removed.

For every participant, event-related potentials (ERPs) were calculated for each deviant and standard by averaging signals for the given stimulus. As standards were presented much more frequently than deviants, the standard presentations that immediately preceded deviant presentations within a given block were included for further analyses. Therefore, the total number of segments for standards comprised approximately 100 trials. As the occipital area was defined as the region of interest, O1, O2, and Oz were pooled into one electrode site. Individual difference waves (vMMN) for each participant were calculated by subtracting the average signal of standard from the average signal of deviant. The data were then exported from BrainVision Analyzer as numeric values. The amplitudes of ERPs elicited by deviant and standards were averaged in 20 ms time intervals of interest, constituting 15 time intervals (60-360 ms post stimulus). The individual vMMNs were also exported as numeric values and averaged within three time intervals. Subsequently, vMMN peak amplitudes and latencies were also examined within these intervals.

Statistical analyses

Statistical analyses were conducted in the statistical computing R environment 3.2.3 and IBM SPSS Statistics 20.0 (IBM Corp., Armonk, New York, United States). Paired sample t-tests were used to see whether the mean level of blood glucose levels and subjective hunger ratings differ between the two conditions. Repeated measures analysis of variance (ANOVA) was conducted to examine whether there is a difference between the deviant and its immediate preceding standard. Repeated measures ANOVAs were also used to examine whether there is a difference between the two conditions regarding the vMMN peak latency and peak amplitude.

For the EBA task, the answers which reaction times remained below 100 or above 1000 ms were removed from the analyses. For lag 2 and 4, only trials in which the participant was correct

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at assessing the presence and direction of the rotation of the target stimulus were considered correct. For lag 0 (no distractor stimulus), only responses to the first question (i.e., presence of a target) were examined as the answer to the second question (i.e., direction of the rotation of the target stimulus) was automatically assumed to be incorrect. Therefore, answers for lag 0 were correct when the participant was correct at assessing the presence of a distractor. The percentage of correct trials was calculated for each participant within each category (e.g., HFSA and lag 2). A repeated measures ANOVA was conducted to explore whether the percentage of correct trials differs between conditions and stimulus categories.

All repeated measures ANOVAs were conducted with the „lme“ function from the „nlme“ package. Subsequently, pairwise comparisons with the Holm-Bonferroni method for multiple comparisons were conducted with „lsmeans“ function from the „lsmeans“ package. Spearman rank-order correlation analyses were conducted in SPSS to see whether the peak amplitudes of the mismatch responses in HFSA and HFSW within the three time windows are associated with the percentage of correct trials in EBA at lag 2 (200 ms), EDAS total and subscale scores, subjective hunger ratings, and the appetitiveness and attention-elicitation ratings of the stimuli used in the EEG experiment.

RESULTS

Hunger manipulation

The differences in blood glucose levels and subjective hunger ratings showed that the hunger manipulation was successful. There was a significant difference between the blood glucose level measured upon arriving at the lab and blood glucose level measured after breakfast [$t(17) = -8.28, p < .0001$], with the mean blood glucose level being lower upon arriving at the lab hungry. Participants in the fed condition also had significantly lower subjective hunger ratings than participants in the hunger condition [$t(17) = 9.95, p < .0001$], with the mean subjective hunger level for the fed condition being 6.22 (SD = 7.89) and 58.0 (SD = 18.69) for the hunger condition. There were no differences in the subjective hunger and blood glucose levels between the two conditions upon arriving at the lab. Additionally, subjective hunger levels measured after the EEG experiment were compared between the two conditions to test whether the hunger manipulation was also applicable to the subsequent EBA task. In the subjective hunger levels measured after the EEG experiment, there was a significant difference between the two groups [$t(17) = -10.79, p < .0001$], with the mean score for hunger condition being 73.73 (SD = 15.02) and 16 (SD = 19.45) for the fed condition.

2-back working memory task

In case the participant did not manage to press the left or right side of the mouse, the response was categorized as missing. In total, there were 2.3% of missing responses. The percentage of missed responses did not differ between the conditions ($p = .3269$) and blocks ($p = .5510$). Missed responses were left out from subsequent analyses. The percentage of correct responses did not differ between the conditions ($p = .5101$). There was, however, a significant difference between the blocks [$F(1,51) = 13.91, p = .0005$], indicating that participants in the HFSA block performed slightly better than in the HFSW block. The percentage of correct responses for the HFSA was 91% and for HFSW 89%.

Differences between deviants and standards

In order to reduce the amount of statistical comparisons, six separate models pertaining to repeated measures ANOVA were tested for each deviant and standard stimulus to determine

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whether there is a difference between the deviant and its immediate preceding standard. Thus, stimulus type (deviant, its preceding standard), 15 intervals (60-360 ms), and condition (hunger, fed) were entered into the model as within-subjects variables. The averaged signal from the pooled occipital electrode site was entered into the model as the dependent variable.

Regarding the HFSA block, there was a main effect of interval [$F(14,1003) = 7.98, p < .0001$], condition [$F(1,1003) = 30.68, p < .0001$], and a significant interaction between stimulus and interval [$F(14,1003) = 7.60, p < .0001$] for the first food deviant (D1). Regarding the second food deviant (D2), a significant main effect of interval [$F(14,1003) = 8.18, p < .0001$] and condition [$F(1,1003) = 10.08, p = .0015$], and significant interactions between stimulus and interval [$F(14,1003) = 2.44, p = .0022$], and stimulus and condition [$F(1,1003) = 6.03, p = .0142$] were observed. For the neutral deviant (D3), there was a main effect of interval [$F(14,1003) = 8.57, p < .0001$] and condition [$F(1,1003) = 10.96, p = .0010$], whereas no significant interactions were observed.

Regarding the HFSA block, there was a main effect of interval [$F(14,1003) = 6.01, p < .0001$], and a significant interaction between stimulus and interval [$F(14,1003) = 2.68, p = .0007$] for the first food deviant (D1), whereas the difference between conditions was not significant. The main effect of interval [$F(14,1003) = 7.36, p < .0001$] and condition [$F(1,1003) = 11.24, p = .0008$], and a significant interaction between stimulus and condition [$F(1,1003) = 9.26, p = .0024$] were observed for the second food deviant (D2). For the neutral deviant (D3) there was a main effect of interval [$F(14,1003) = 5.80, p < .0001$] and condition [$F(1,1003) = 13.56, p = .0002$]. No significant interactions were found.

Next, pairwise comparisons were conducted to detect the intervals where the average signal of the deviant was statistically different from the average signal of the standard (ie., vMMN occurred). The results of the pairwise comparisons are presented in Table 1. Deviant minus standard difference waveforms are depicted in Figure 4 and Figure 5.

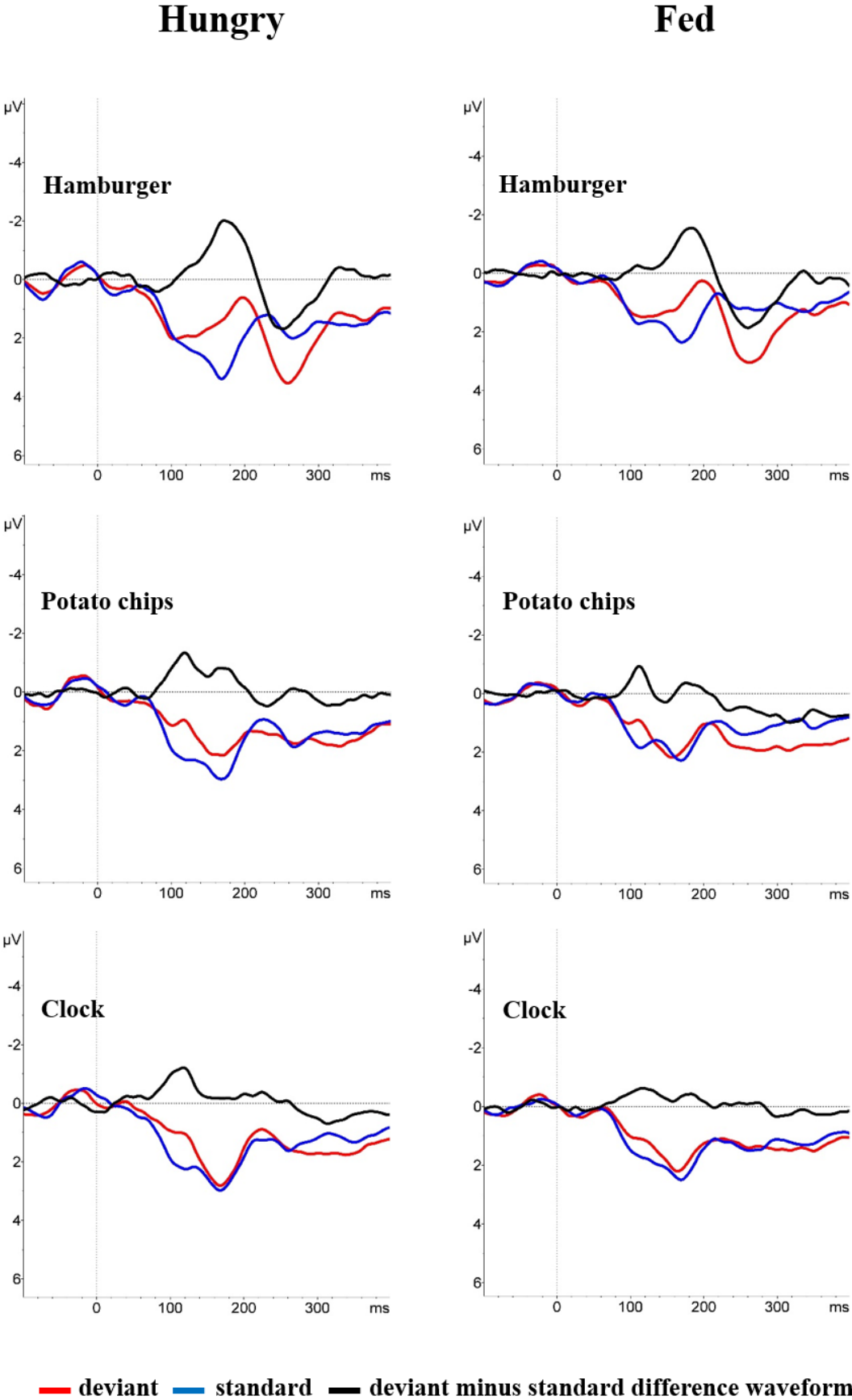


Figure 4. Grand average ERP waveforms of the pooled occipital electrode site for the three deviants in the HFSA block for hunger and fed conditions separately.

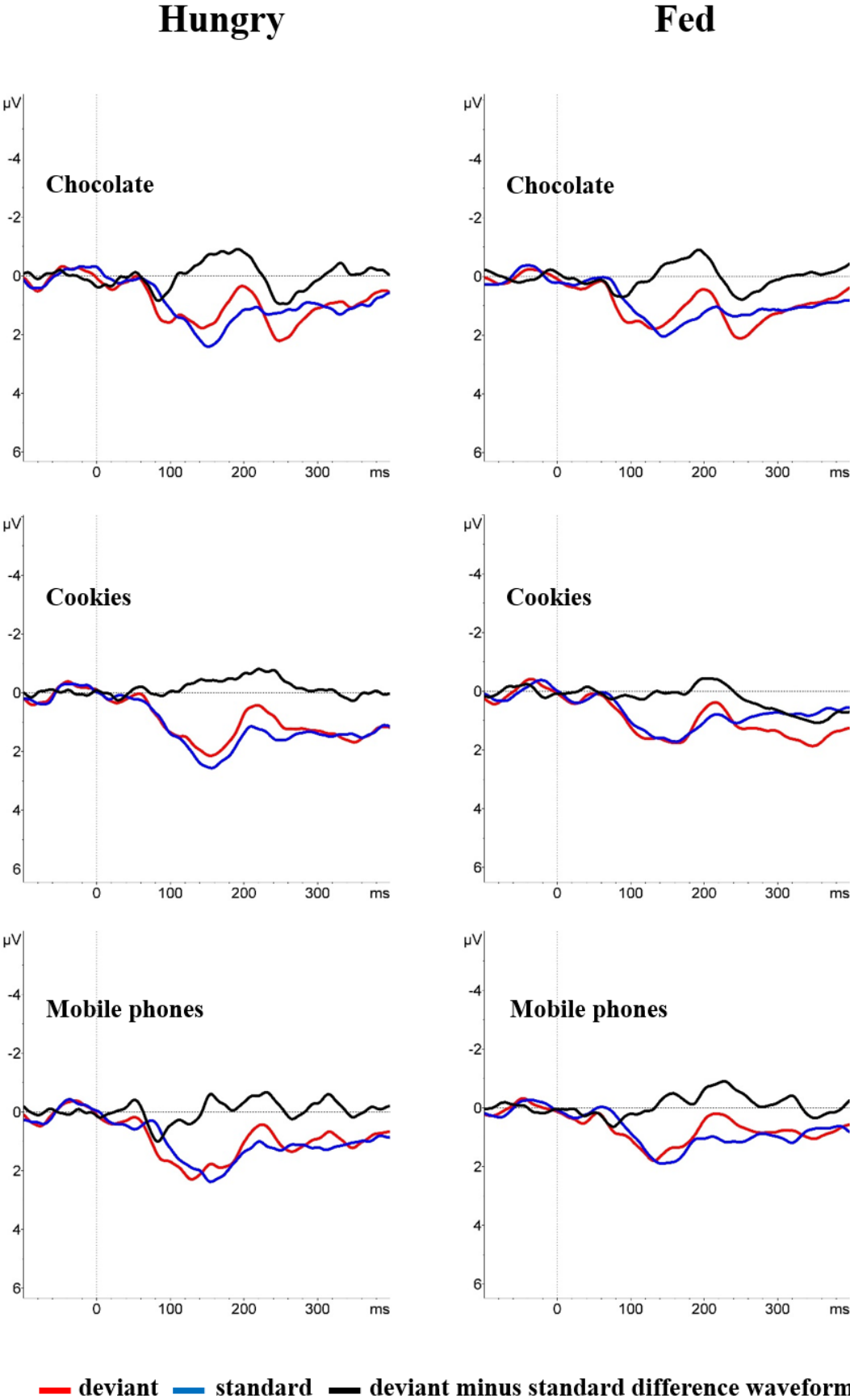


Figure 5. Grand average ERP waveforms of the pooled occipital electrode site for the three deviants in the HFSW block for hunger and fed conditions separately.

Table 1. Differences between deviants and standards within 15 time intervals. Results are averaged across conditions.

Deviant	Time interval post stimulus (ms)														
	60-80	80-100	100-120	120-140	140-160	160-180	180-200	200-220	220-240	240-260	260-280	280-300	300-320	320-340	340-360
HFSA															
D1					**	**	**		**	**	**	*			
D2			**											*	
D3			*												
HFSW															
D1		*				*	**			**					
D2															*
D3								*	*						

Note: * - $p < .05$, ** - $p < .01$, */** - positive difference, */** - negative difference.

Differences in mismatch responses across conditions, stimuli, and time latencies

As no mismatch response studies have yet been conducted with visual food stimuli, we cannot rely on previous studies to determine the appropriate time windows to test our hypotheses. In order to avoid the researcher bias in selecting the time windows, we used a collapsed localizer approach as suggested by Luck & Gaspelin (2017). For this purpose, a grand average waveform for each block (e.g., HFSA) was calculated by averaging the mean amplitudes of mismatch responses related to the three deviants in each block (e.g., HFSA) across both conditions (hunger, fed). Therefore, two grand average waveforms were calculated. The grand average waveforms for HFSA and HFSW are depicted in Figure 6.

Next, measurement windows for subsequent analyses were selected by visually inspecting the grand average waveforms. Based on visual inspection, three prominent intervals for the mismatch negativity/positivity emerged. In both blocks, there appear to be two peaks in earlier latencies and one peak in the late latency. The mismatch responses, however, appear to be elicited in separate time windows in HFSA and HFSW. Therefore, in HFSA, the early (100-160 ms) and mid-latency (160-220 ms) time windows constitute the elicitation of mismatch negativity responses, and the late time window (220-360 ms) corresponds to the elicitation of a mismatch positivity response. Similarly, in HFSW, the early (120-180 ms) and mid-latency (180-240 ms) time windows constitute the elicitation of mismatch negativity responses, and the late time window (240-300 ms) corresponds to the elicitation of a mismatch positivity response.

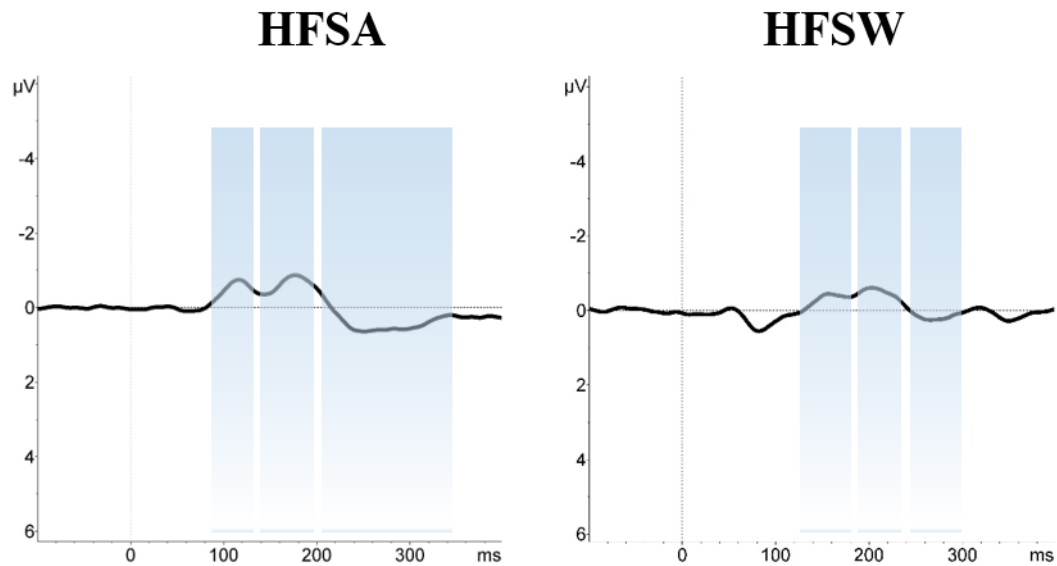


Figure 6. Grand average waveforms depicting the average amplitudes of the mismatch responses across two conditions and three deviants in HFSA and HFSW. Three time windows selected for further analyses are highlighted.

In order to investigate the processes related to the mismatch responses, a repeated measures ANOVA was conducted to see whether the peak amplitude and its latency differ between the stimuli in the HFSA and HFSW blocks. For this purpose, predefined latencies referring to early, mid-latency, and late time windows were selected. Stimulus (D1, D2, D3) and condition (hunger, fed) were entered into the model as within-subjects variables, and the individual mismatch response peak amplitude or latency as the dependent variable. For latencies and amplitudes, separate models were conducted. This resulted in six models tested for HFSA and HFSW separately. The results of the repeated measures ANOVAs are presented in Table 2.

Early time window

In HFSA, the average peak latency was significantly shorter for D1 in comparison to D2 [$t(85) = -4.28, p < .0001$] and D3 [$t(85) = -2.82, p = .0120$], indicating that the attention was first allocated to D1. The average negative peak was also significantly larger in the hunger in comparison to the fed condition [$t(85) = 3.13, p = .0024$], indicating that hunger biased the attention towards all the stimuli in HFSA. In HFSW, no main differences between conditions and stimuli were found regarding peak amplitudes and latencies.

Table 2. The results of the repeated measures ANOVAs pertaining to the peak latencies and peak amplitudes of the mismatch responses in HFSA and HFSW.

	HFSA						HFSW					
	Early time window											
	Peak amplitude			Peak latency			Peak amplitude			Peak latency		
	df	F	p	df	F	p	df	F	p	df	F	p
Condition	1,85	9.81	.0024	1,85	.07	.7908	1,85	.54	.4649	1,85	.70	.4061
Stimulus	2,85	.33	.7174	2,85	9.46	.0002	2,85	1.81	.1699	2,85	1.73	.1820
	Mid-latency time window											
	Peak amplitude			Peak latency			Peak amplitude			Peak latency		
	df	F	p	df	F	p	df	F	p	df	F	p
Condition	1,85	4.78	.0315	1,85	1.26	.2657	1,85	.70	.4040	1,85	.33	.5691
Stimulus	2,85	26.02	.0001	2,85	3.66	.0299	2,85	1.01	.3672	2,85	26.69	.0001
	Late time window											
	Peak amplitude			Peak latency			Peak amplitude			Peak latency		
	df	F	p	df	F	p	df	F	p	df	F	p
Condition	1,85	.03	.8572	1,85	.34	.5606	1,85	.57	.4508	1,85	.89	.3478
Stimulus	2,85	7.40	.0011	2,85	8.54	.0004	2,85	2.88	.0616	2,85	6.86	.0017

Mid-latency time window

In HFSA, the average negative peak across all stimuli was significantly larger in hunger in comparison to the fed condition [$t(85) = 2.19$, $p = .0315$]. This indicates that hunger biased attention towards all the stimuli. The negative peak of D1 was also significantly larger than the negative peak of D2 [$t(85) = -6.38$, $p < .0001$] and D3 [$t(85) = -6.10$, $p < .0001$], indicating that the first food stimulus in HFSA was allocated more neuronal resources related to attentional processing compared to other deviants. Further, in comparison to D3, D1 peaked later [$t(85) = 2.69$, $p = .0257$]. In HFSW, no differences in peak amplitudes were found between the conditions and stimuli. Regarding peak latencies, the peak latency for D1 was longer than the peak latency for D2 [$t(85) = 4.68$, $p .0001$] and D3 [$t(85) = 4.48$, $p .0001$]. Further, the peak latency for D2 was also longer than the peak latency for D3 [$t(85) = 4.48$, $p = .0135$].

Late time window

In HFSA, there was a main effect of stimulus regarding peak latencies and amplitudes. The average peak latency for D1 was significantly shorter than the average peak latency for D2 [$t(85) = -2.98, p = .0075$] and D3 [$t(85) = -3.97, p = .0004$]. Moreover, the positive peak of D1 was significantly larger than the positive peak of D2 [$t(85) = 3.29, p = .0034$] and D3 [$t(85) = 3.39, p = .0034$], demonstrating again that the first food stimulus received more neuronal resources pertaining to attentional processing in comparison to other deviants. No differences between conditions in HFSA were found. In HFSW, the peak latency for D1 was significantly shorter than for D2 [$t(85) = -3.30, p = .0042$] and D3 [$t(85) = -3.10, p = .0052$], whereas no differences between the conditions were found regarding peak latencies and amplitudes.

Emotional blink of attention

The percentage of correct numbers in EBA was subjected to a four-factor repeated measures ANOVA with condition (hunger, fed), block (HFSA, HFSW, neutral), lag (0, 2, 4) as within-subjects variables, and the order of conditions (hunger first, fed first) as the between-subjects variable. There was a main effect of condition [$F(1,238) = 5.20, p = .0234$], and lag [$F(2,238) = 26.33, p < .0001$], but no effect of block or the order of conditions. There was also a significant interaction between condition and lag [$F(2,238) = 4.06, p = .0184$]. Contrary to what we expected, the percentage of correct trials was higher during hunger in comparison to the fed condition [$t(238) = -2.57, p = .0109$]. Participants also had more correct trials at lag 0 compared to lag 2 [$t(238) = 5.92, p < .0001$] and lag 4 [$t(238) = 7.07, p < .0001$].

Exploratory correlation analyses

Spearman rank-order correlations were conducted to investigate the associations between the peak amplitudes of deviants in early, mid-latency, and late time windows in hunger and fed conditions, and EDAS total and subscale scores, appetitiveness, attention-elicitation and subjective hunger ratings, BMI and the percentage of correct responses in EBA at lag 2 (200 ms). The results of the correlation analyses are presented in Table 3-6. Further, only significant correlation coefficients are presented.

There were significant correlations between the peak amplitudes of deviants in the early, mid-latency, and late time windows and appetitiveness and attention-elicitation ratings given to D2 in the hunger condition. For example, appetitiveness ratings of D2 were negatively correlated with the peak amplitude of D2 in the early latency and D1 in the mid-latency time window. Therefore, higher appetitiveness ratings given to D2 was associated with a larger mismatch negativity. Further, the subjective hunger before the experiment in hunger was negatively correlated with the peak negative amplitude of D1 in the early time window, indicating that higher subjective hunger was associated with a larger mismatch response to the hamburger.

As the sample size was relatively small, the correlation coefficients could be unstable or biased towards false positives. This is evident in the correlations between EDAS total and subscale scores and the peak amplitudes of deviants. For example, there is a significant negative correlation between EDAS subscale Binge eating and the peak amplitude of D1 in HFSW during hunger, indicating that those who score higher on Binge eating, demonstrate larger mismatch negativity in response to D1. However, the correlation between Binge eating and the peak amplitude of D1 in the mid-latency in HFSA during hunger is positive, indicating that those who score higher on the Binge eating subscale, show less mismatch negativity.

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Table 3. Spearman rank-order correlation coefficients between the peak amplitudes of the mismatch responses in HFSA during hunger in early, mid-latency, and late time windows, and EDAS total and subscale scores, subjective hunger, appetitiveness and attention-elicitation ratings, and BMI.

Measures	Early time window			Mid-latency time window			Late time window		
	D1	D2	D3	D1	D2	D3	D1	D2	D3
Appetitiveness – D2		-.58*		-.50*					
Attention – D1		-.47*	-.58*						
Attention – D2		-.56*	-.58*	-.62*		-.52*	.52*	.61**	
Subjective hunger before the experiment	-.52*								
EDAS total								.50*	
Binge eating (EDAS)				.48*					
Restrained eating (EDAS)								.64**	
EBA – lag 2			-.49*						
BMI									.52*

Note: ** - correlations are significant at $p < .01$; * - correlations are significant at $p < .05$.

Table 4. Spearman rank-order correlation coefficients between the peak amplitudes of the mismatch responses in HFSA during the fed condition in early, mid-latency, and late time windows, and EDAS total and subscale scores, and attention-elicitation ratings.

Measures	Early time window			Mid-latency time window			Late time window		
	D1	D2	D3	D1	D2	D3	D1	D2	D3
Attention – D2					-.47*				
Attention – D3							-.55*		
EDAS total						.48*			
Binge eating (EDAS)		.64**							
Preoccupation with body image and body weight (EDAS)						.51*			

Note: ** - correlations are significant at $p < .01$; * - correlations are significant at $p < .05$.

Table 5. Spearman rank-order correlation coefficients between the peak amplitudes of the mismatch responses in HFSA during hunger in early, mid-latency, and late time windows, and EDAS total and subscale scores, attention-elicitation ratings, and blood glucose levels upon arrival.

Measures	Early time window			Mid-latency time window			Late time window		
	D1	D2	D3	D1	D2	D3	D1	D2	D3
Attention – D2								.47*	
Blood glucose upon arrival			.47*						.51*
EDAS total				-.59**					
Binge eating (EDAS)				-.66**			-.61**		
Preoccupation with body image and body weight (EDAS)							-.51*		

Note: ** - correlations are significant at $p < .01$; * - correlations are significant at $p < .05$.

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Table 6. Spearman rank-order correlation coefficients between the peak amplitudes of the mismatch responses in HFSW during the fed condition in early, mid-latency, and late time windows, and EDAS subscale Binge eating, BMI, attention-elicitation ratings, and blood glucose levels after breakfast.

Measures	Early time window			Mid-latency time window			Late time window		
	D1	D2	D3	D1	D2	D3	D1	D2	D3
Attention – D3									-.48*
Blood glucose after breakfast			-.77**						
Binge eating (EDAS)									-.58*
BMI						-.61**			.53*

Note: ** - correlations are significant at $p < .01$; * - correlations are significant at $p < .05$.

DISCUSSION

In the present study, we investigated whether presenting visual food stimuli in an oddball paradigm elicits visual mismatch responses, and whether the elicited mismatch responses differ between hunger and fed conditions. For this purpose, food stimuli depicting high fat savoury and high fat sweet foods were presented to participants in an oddball paradigm. Further, emotional blink of attention was used to validate the results pertaining to the mismatch responses.

First, we aimed to investigate whether presenting visual food stimuli as deviants elicits visual mismatch responses during hunger and fed conditions. This hypothesis was partially confirmed. We found significant differences between food deviants and standards in the early, mid-latency, and late processing stages. Nevertheless, some deviants elicited more mismatch responses than others. Specifically, we found that the first food deviant in HFSA elicited mismatch responses in the approximate latencies of 140-200 ms and 220-300 ms, whereas the second food deviant elicited mismatch responses in the latencies of 100-120 ms and 300-320 ms. In HFSW, the first food deviant elicited mismatch responses in the latencies of 160-200 ms and 240-260 ms. The second food deviant in HFSW, on the other hand, elicited mismatch responses only in the latency of 340-360 ms. As the processing of early and mid-latency ERP components has been linked to selective attention (Olofsson et al., 2008), it is plausible that both food deviants in HFSA and the first food deviant in HFSW elicited automatic attention allocation in our study. This is further in line with the EEG studies that have demonstrated that the automatic orientation towards food stimuli could occur as early as 165 ms (Toepel et al., 2009), 170 (Stockburger et al., 2008), and even 70 ms (Stockburger, Schmälzle, Fleisch, Bublatzky, & Schupp, 2009a) in the posterior electrode site. Further, neutral deviants also elicited mismatch responses, but, for instance, for the neutral deviant in the HFSA block, the vMMN occurred early (100-120 ms) and disappeared subsequently. Thus, it is plausible that very early ERPs elicited by neutral deviants might correspond to the discrimination of stimuli based on physical stimulus features.

The second hypothesis postulated that the amplitude of the vMMN elicited by food stimuli in the occipital area is larger during hunger in comparison to fed condition. This hypothesis received partial confirmation. To begin with, we found that hunger modulated the peak amplitude of the mismatch response only in HFSA. In HFSA, the modulation of hunger was seen in the early and mid-latency time windows related to mismatch negativity. Therefore, we

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could demonstrate that during hunger, all stimuli received more attentional processing in the early processing stage pertaining to automatic attention. In addition, the first food deviant, i.e., hamburger, was clearly different from other stimuli in the block, eliciting the largest negative peak amplitude in the mid-latency and largest positive peak amplitude in the late time window. Thus, the question arises whether the differences in elicited vMMN amplitudes are present because D1 is a highly salient food stimulus. The peak negativity of D1 during hunger in the early latency correlated with subjective hunger. Thus, it is plausible that hamburger elicited mismatch responses due to its motivational salience. Alternatively, D1 could also be the most visually distinct stimulus within that block, as the differences between the two food deviants were also found in early, mid-latency, and late time windows. Even though the peak amplitudes of D2 in HFSA did not differ significantly from the peak amplitudes of D3, it could still be argued that D2 was also differently processed than D3. In particular, the appetitiveness ratings of D2 were significantly correlated with the peak negativity of D2 in the early latency in hunger. Some studies have also found that food deprivation biases attention towards food stimuli in comparison to neutral stimuli in a similar latency range (100-220 ms) corresponding to automatic attention as reported in our study (Stockburger, Schmäzle, Fleisch, Bublatzky, & Schupp, 2009b; Stockburger et al., 2008). Thus, the automatic attention allocation to food stimuli might have taken place in our study, but the effect pertaining to D2 might be less pronounced as D1 was more appetizing and also visually distinct.

The possibility of the influence of hunger on neutral stimulus processing cannot also be ruled out, as the mismatch negativity elicited by the neutral deviant in HFSA was also influenced by hunger. Thus, it is plausible that MMN could be sensitive to condition. For example, Kremlacek et al. (2016) conducted a review of studies pertaining to differences in vMMN among psychiatric and neurological disorders. Curiously, even though very few studies used disease-specific stimuli (e.g., threat-related stimuli among anxiety disorders), significant differences among various conditions in comparison to healthy individuals emerged. Thus, MMN seems to be a sensitive method for the detection of changes in the general information processing. Therefore, similarly to some other condition, hunger could constitute a condition that is different from the baseline.

Regarding the HFSW block, we could not demonstrate the modulation of hunger on food cue processing. Further, we found that the first deviant differed in its peak latencies from the other two stimuli in mid-latency and late time windows. Nevertheless, no differences in peak

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amplitudes were observed. Therefore, similarly to the HFSA block, the food deviants seem to differ in their vMMN elicitation properties. Furthermore, it is not clear why the modulation of hunger was only emerged in the high fat savoury block. There is a possibility that high fat savoury foods are differently processed than high fat sweet foods. Specifically, fat content is proposed to be a factor that strongly influences palatability of the food and body's energetic balance (Drewnowski, 1998; Rolls, 2007). Nevertheless, this assumption is unlikely as numerous studies have demonstrated that high-calorie sweet and savoury foods are both differently processed than low-calorie foods, especially during fasting (Goldstone et al., 2009; Killgore et al., 2003). More likely explanation could be attributed to the fact that the two blocks differed in how similar the stimuli were. Even though the physical features of the stimuli regarding contrast and luminance were matched within blocks, the images in the HFSW block were more similar with each other. In HFSA, there was more variation in terms of colour and shape. Thus, as the participant was instructed to direct attention away from the periphery where the images were presented, it is plausible that some kind of visual dissimilarity is needed to be able to automatically discriminate between the stimuli.

Unfortunately, we could not validate vMMN via emotional blink of attention paradigm. Contrary to what we expected, we found that participants in the hunger condition had more correct responses in the EBA task. Hence, all stimuli, including neutral ones, captured more attentional resources in the fed condition. Previously, it has been suggested that attentional blink might be sensitive to interindividual differences (MacLean & Arnell, 2010). Thus, perhaps there could have been some confounding factors in our study related to individual differences that interfered.

There are a few limitations of the current study. To begin with, the sample size was relatively small. Therefore, we found that our exploratory correlation analyses yielded some mixed results. In addition, only women were included in our analyses. Further, it has been demonstrated that the menstrual cycle influences brain responses to food images (Alonso-Alonso et al., 2011). Thus, directly controlling for the menstrual cycle could also have provided different results. We also used only two food stimuli in each block. For that reason, we cannot conclude whether the elicited mismatch response is evoked in response to a specific food category (e.g., HFSA) or food (e.g., hamburger). Nevertheless, examining the results of the equiprobable design could help shed light on this question. In particular, the mismatch response to a particular stimulus elicited in the oddball block could be compared to the mismatch

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response to a particular stimulus elicited in the equiprobable block. When the deviant elicits similar responses in both blocks, it could be argued that the evoked mismatch response emerged because such affective stimulus as food was differently processed from other stimuli.

There are also several implications for the future. We did find some significant correlations between binge eating and the peak amplitudes regarding food stimuli in the early and mid-latency time windows. Therefore, it is plausible that the automatic attention allocation towards disease-specific stimuli could be influenced by eating disorder related features. As early attentional bias towards food has also been demonstrated in eating disorder literature (Wolz et al., 2015), vMMN could provide to be a reliable measure that could also be used in the assessment of eating disorder features after further validation.

In conclusion, we investigated whether the presentation of visual food stimuli elicits visual mismatch responses and whether this differs between hunger and fed conditions. We found that deviant minus standard difference waveforms yielded significant negativities in the early and mid-latency, and significant positivities in the late time window. The modulation of hunger was evident in HFSA, but not in HFSW. In addition, even though the effect of hunger was witnessed in HFSA, food deviants in HFSA differed in their vMMN elicitation properties. Moreover, hunger also modulated the processing of neutral deviant. Therefore, it is also plausible that hunger influences general information processing. In conclusion, vMMN might prove to be a reliable measure in investigating automatic food-cue processing after additional attempts at vMMN validation with different food stimuli have been conducted.

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