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Modulation of event-related potentials to food cues upon sensory-specific satiety

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ABSTRACT

Tempting environmental food cues and metabolic signals are important factors in appetite regulation. Food intake reduces liking of food cues that are congruent to the food eaten (sensory-specific satiety). With this study we aimed to assess effects of sensory-specific satiety on neural processing (perceptual and evaluative) of visual and olfactory food cues.

Twenty healthy female subjects (age: 20 ± 2 years; BMI: 22 ± 2 kg/m^2) participated in two separate test sessions during which they consumed an *ad libitum* amount of a sweet or savoury meal. Before and after consumption, event-related potentials were recorded in response to visual and olfactory cues signalling high-energy sweet, high-energy savoury, low-energy sweet and low-energy savoury food and non-food items.

In general, we observed that food intake led to event-related potentials with an increased negative and decreased positive amplitudes for food, but also non-food cues. Changes were most pronounced in response to high-energy sweet food pictures after a sweet meal, and occurred in early processes of perception (~80–150 ms) and later processes of cognitive evaluation (~300–700 ms).

Food intake appears to lead to general changes in neural processing that are related to motivated attention, and sensory-specific changes that reflect decreased positive valence of the stimuli and/or modulation of top-down cognitive control over processing of cues congruent to the food eaten to satiety.

1. Introduction

With an abundance of tempting environmental cues (*e.g.* visual, olfactory), effective regulation of food intake is vital. Sensory properties of food play an important role in the selection of food for adequate and diverse nutrient intake, but also in the cessation of eating [17,31]. With this study we aim to get a better understanding of the neural processes involved in the interplay between metabolic and sensory factors involved in appetite control and food intake regulation.

When a particular food item is consumed to satiety, the hedonic value of the sensory cues (tastes, odours) related to that food item declines, while liking of food items that have not been consumed does not decrease, or decreases to a lesser extent [22,24]. This phenomenon is referred to as sensory-specific satiety. It decreases the likelihood of continued intake of foods with the same or similar sensory characteristics. Hence, sensory-specific satiety is thought to promote a more varied diet [12,24,37].

Sensory-specific satiety has been extensively described using subjective measures of liking and food intake, but the underlying neural mechanisms need more clarification. Previous research revealed sensory-specific satiety related changes in facial expressions and skin conductance that indicate increased boredom upon consumption of a food item (*i.e. gazpacho, pea-spinach soup, mango smoothie and strawberry juice*) that was previously eaten to satiety [7]. Neuroimaging studies revealed decreased orbitofrontal cortex activation upon sensory-specific satiety ([22], *using bananas*; [29], *using chocolate*). These changes were related to decreased reward, or increased aversion, when people did not want to eat more of the food item. Moreover, changes in perception of odour intensity after food intake have been related to sensory-specific satiety ([25,26], *using chicken and banana*). Together these results suggest that sensory-specific satiety has modulatory effects on processes of sensory perception as well as hedonic evaluation. Increased understanding of the modulatory role of food intake on different stages of neural processing of food cues is required.

The dynamics of neural processing from early stages of perception to later stages of cognitive evaluation can be captured using electro-encephalography (EEG). Several EEG studies have reported decreased amplitudes in later neural processing stages (P3; ~300–500 ms)

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elicited by visual food cues after food intake, and have associated this decrease with reduced motivated allocation of attention to food cues [14,19–21,32]. It is proposed that internal state modulates neural processes of attention and reward, and thereby stimulates behaviours aimed at restoring energy levels [28,32], perhaps also in a sensory-specific fashion.

Previous EEG research into food cue processing has focused on general effects of hunger. Moreover, to our knowledge, previous studies into sensory-specific satiety have not used EEG to gain insight into effects on neural processing. The innovative nature of the current study is associated with a lack of comparable previous research to base specific *a priori* hypotheses on. We therefore employ a more exploratory approach.

With this study we aimed to evaluate the effects of sensory-specific satiety on the perceptual and evaluative neural processing of visual and olfactory food cues. Taste as well as energetic value has been found to influence behavioural and brain responses to food cues [15,34,38]. During the anticipation of food intake these types of cues are highly important in food selection and intake behaviour. In light of phenomena like external eating, we take a particular interest in the food cue responses after food intake. We hypothesized that food intake would lead to a general decrease in amplitude for late event-related potentials, which reflect changes in evaluative processes, and that this effect will be most pronounced for food cues that are congruent to the food eaten to satiety (*i.e.* sensory-specific satiety). We did not expect to find changes in early event-related potentials, related to perceptual processing.

2. Materials and methods

2.1. Overall design

This study followed a within-subject design, including the factors time of test (pre−/post-meal) and stimulus category (high-energy sweet: HESw, high-energy savoury: HESav, low-energy sweet: LESw, low-energy savoury: LESav, non-food control: NF, and no-odour/empty white disc control: baseline). We looked at the effects of meal type ingested (sweet/savoury) and used cues of two stimulus modalities (visual/olfactory). Given the aim of this study (to investigate sensory-specific satiety), we focused our analyses on the effects of meal type ingested on neural processing of cues belonging to a single stimulus category. We did not focus on interaction effect between meal type ingested and stimulus categories or stimulus modalities.

2.2. Participants

Twenty normal-weight females (age: 20 ± 2 years; Body Mass Index (BMI): 22 ± 2 kg/m^2) participated in this study. Included participants were normosmic (scoring ≥12 on the Sniffin' Sticks 16-item identification test; [11], in general good subjective health, not using medication other than paracetamol and oral contraceptives, were weight stable for at least two months and were not considered restrained eaters (score ≤ 2.8 on the Dutch Eating Behaviour Questionnaire; [35,36]). We also did not include participants that had a smoking habit, had convictions that restricted consumption of certain food items (*e.g.* vegetarian, vegan) or a mental or physical status that could hinder the study procedures (*e.g.*, food allergy, epilepsy). Respondents that did not like the food items used in the study (< 40 mm on a 100 mm Visual Analogue Scale (VAS)) or did not like the odours used in the study (< 30 mm 100 mm VAS) were excluded. Participants received monetary compensation for completing the study. All participants provided written informed consent before they participated in the study. This study was conducted in accordance with the Declaration of Helsinki of 1975, revised in 2013. The protocol was approved by the Medical Ethical Committee of Wageningen University (NL52713.081.15).

2.3. Experimental procedure

Participants took part in two separate test sessions during which event-related potentials were acquired before and after meal intake. Test sessions were separated by a 'washout' period of at least two days. For each participant, the two test sessions took place at approximately the same time of day: 9:00–12:00, 12:00–15:00, or 15:00–18:00. Each participant received a sweet meal in one test session and a savoury meal in the other. The order of the meals was counterbalanced over all participants. Participants were instructed not to eat and drink anything but water and weak tea in the three hours before the test session. Upon arrival, they were seated in a comfortable chair and the EEG equipment was fitted. Before the EEG paradigm started, participants rated their hunger, fullness, prospective consumption, desire to eat, and thirst on a 100 mm VAS and filled in an appetite questionnaire (100 mm VAS; see [38]). The EEG paradigm lasted approximately one hour, divided over six separate blocks with short breaks in between to stay focused. During the blocks, event-related potentials to visual and olfactory stimuli were recorded. After completion of the first EEG paradigm the equipment was disconnected and an *ad libitum* sweet (chocolate flavour) or savoury (flavoured with beef gravy) rice meal with equal energy density and similar macronutrient content (± 800 kCal; ± 575 g; see nutritional values in Table 1) and 200 mL of tap water were provided. Participants were instructed to eat as much as they wanted and to drink all of the water. When they were satiated (± 15 min after meal intake started), the equipment was connected again and the EEG paradigm was repeated. Missing values for food intake occurred for one participant in the savoury meal session. Further, for one participant data of the hunger ratings and appetite questionnaire for the savoury meal session were omitted because post-meal ratings were provided at a later point in the experimental procedure compared to other participants.

2.4. Appetite questionnaire

Participants provided ratings (100 mm VAS) of their general appetite and their appetite for 15 different food items in five categories (HESw, HESav, LESw, LESav, Neutral; see supplementary Table 1; [38]). The order in which the food items were presented was randomized. HESw food items included pieces of chocolate, cake and stroopwafel (a Dutch caramel syrup waffle); HESav food items included beef croquette, cheese cubes and crisps; LESw food items included a slice of melon, an apple and strawberries; LESav food items included a piece of cucumber, tomato salad and raw carrot; bread, croissants and pancake were included as taste neutral food items.

2.5. Olfactory stimuli

We used odours signalling either HESw, HESav, LESw, and LESav food, and included a non-food (NF) odour and a no-odour baseline solution as controls (see [38]). The selected odours included chocolate (HESw; International Flavors and Fragrances (IFF) 10,810,180; 5% in Propylene Glycol (PG)), beef (HESav; IFF 10878095; 0.08% in demi water), melon (LESw; IFF 15025874; 10% in PG), cucumber (LESav; IFF 73519595; 100%), fresh green (NF; AllSens–Voit Aroma Factory No.

Table 1
Nutritional values per 100 g of the sweet and savoury rice meals.

Nutrients	Sweet	Savoury
Energy (kcal)	141	139
Protein total (g)	2.4	2.4
Fat total (g)	3.2	3.2
Carbohydrates total (g)	25.1	25.0
Mono- and disaccharides total (g)	14.7	1.8
Dietary fibres total (g)	1.0	0.2
Sodium (mg)	20	564