Food craving, food choice and consumption: The role of impulsivity and sham-controlled tDCS stimulation of the right dlPFC

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ABSTRACT

Background: Impulsivity has been found to be associated with overeating and obesity. Transcranial direct current stimulation (tDCS) may enhance inhibitory control while reducing food craving and intake. Thus, the aim of the present study was to investigate whether tDCS stimulation modifies food choice, craving and consumption as a function of trait impulsivity.

Methods: Forty-two predominantly healthy-weight women received active tDCS stimulation to the right dorsolateral prefrontal cortex and sham stimulation in a within participant design. Trait impulsivity was measured with a short form of the Barratt Impulsiveness Scale. Participants completed a computerized food-choice task, during which their mouse movements were traced. Current food craving was measured by a modified version of the Food Cravings Questionnaire-State as well as by desire to eat ratings for food pictures. Food intake was measured in a taste test.

Results: There were no tDCS effects on any of the dependent variables. Trait impulsivity (and non-planning impulsivity in particular) was positively associated with higher calorie intake in the taste test, irrespective of tDCS stimulation.

Conclusion: The current findings question the efficacy of single-session tDCS stimulation of the right dLPFC to reduce food craving, high caloric food choice and calorie intake in non-selected, predominantly healthy weight women. However, they do support the idea that trait impulsivity is related to overeating and, therefore, may be a risk factor for obesity. Future research needs to specify which appetitive behaviors can be modulated by brain stimulation and which populations might profit from it the most.

1. Introduction

Global prevalence rates of overweight and obesity have increased substantially in the past decades [54]. Consumption of processed, palatable foods that are rich in fat and sugar has been identified as a major cause of the increase in overweight, obesity [28,64] and poor health. Self-regulation is required to resist the temptations to indulge in such 'hyperpalatable' foods. Once purchased in the supermarket, unhealthy foods are likely to overtax self-regulation, making such choices an interesting target of investigation. In addition, marked individual differences exist in the ability to exert self-control, and particularly the construct of impulsivity has stimulated much research in this regard.

Impulsivity is a multifaceted construct that can be defined as "a predisposition toward rapid, unplanned reactions to internal or external stimuli without regard to the negative consequences of these reactions" ([52], p. 1784). Accordingly, impulsivity may play a critical role in the etiology and maintenance of obesity and eating disorders [23]. For example, higher impulsivity relates to unsuccessful dieting [48], external eating, i.e., eating driven by external food cues [32], frequent food cravings [46], binge eating (e.g., [41,51]), higher body weight [1,44], prospective weight gain [15,49,53], food intake in experimental laboratory studies ([22]), and fast food consumption [11,19,26]. Similarly, it was found that more impulsive individuals tend to choose a greater portion of tasty, unhealthy foods [35] or hedonically tempting foods [62] than individuals with lower impulsivity in food-related decision tasks.

On a neural level, impulsive food choices are associated with activation in areas involved in reward processing, such as the striatum, amygdala and orbitofrontal cortex (e.g., [2,39,66]). High trait impulsivity appears to represent a disbalance between these reward-sensitive areas and areas involved in cognitive control. Thus, impulsive behavior might be the result from a lack of integration between reward and cognitive control areas [39,68]. One of these cognitive control areas is

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the dorsolateral prefrontal cortex (dlPFC; [65]), which is well accessible to various methods of non-invasive brain stimulation and, accordingly, several studies have investigated the effects of NIBS on self-control and appetitive behaviors [7,21,34,42]. One such non-invasive technique is transcranial direct current stimulation (tDCS): a weak electric current (typically 0.5–2.0 mA) is applied between two electrodes (anode & cathode) affixed to the scalp overlying the cortical regions of interest. The primary mechanism of action is believed to be a polarity-dependent shift of resting membrane potential [6], with anodal stimulation enhancing cortical excitability and cathodal stimulation having the opposite effect [57].

Several studies found reduced food cravings after anodal stimulation of the right dlPFC with the cathode over the left dlPFC (anode right/cathode left), using 2 mA as stimulation intensity [7,17,20,38]. Some of these studies also reported reduced food intake after active tDCS [7,17,40], while others did not [20,38]. One study also found effects on calorie consumption and appetite scores for anode right/ cathode left stimulation while using a lower stimulation intensity (1 mA; [37]). A recent meta-analysis tentatively concluded that tDCS can modify cravings [60] and little is known about the mechanisms behind the modulation of food craving, its consequences (e.g., does tDCS also affect actual food choice and consumption), or its moderators (e.g., do effects depend on individual differences such as impulsivity). However, two more recent meta-analyses cast doubt about the fundamental effectiveness and reliability of tDCS in healthy individuals regarding its neurophysiological effects [30] and its benefits for cognitive tasks [31].

Thus, the present study tested whether tDCS could be an effective intervention for reducing unhealthy food choice, food craving and food intake, as previous research revealed inconsistent findings. Such inconsistencies could be due to individual differences in the stimulation response – modeled by trait impulsivity here – or due to insensitive measures of 'conflict' during food choice in previous studies. The food choice task employed here included repeated, behaviorally relevant choices (e.g., choices were backed up with actual eating) between two food options by moving the mouse over one of the options. Besides choice outcomes, mouse paths were traced during the decision (Mousetracker; [16]), which yields several process measures that could enhance the sensitivity in detecting relevant processes leading up to this behavioral decision [14,27,61].

Based on the literature discussed above, it was expected that active stimulation of the right DLPFC with tDCS would reduce current food craving, desire to eat ratings of high-calorie foods, the number of high-calorie food choices (and associated process tracing measures) on the choice task and respective consumption (*stimulation main effects*). A within-participant, cross-over stimulation design was used. It was further expected that higher impulsivity would be associated with more intense food craving and desire to eat high-calorie foods as well as more high-calorie food choices and consumption in general (*main effect impulsivity*), but importantly, that impulsivity would further interact with tDCS condition: individuals with higher impulsivity were expected to show stronger reductions in these appetitive behaviors as a result of tDCS than those with lower impulsivity (*moderation analysis impulsivity*).

2. Materials and methods

2.1. Participants

Forty-three unselected, predominantly healthy weight, female participants were recruited among students at the University of Salzburg, Austria. Only women were recruited to avoid confounding effects of sex as taste preferences [70] and food cravings [8] differ between men and women. Exclusion criteria were current mental disorders (including eating disorders), a history of migraine, epilepsy, brain lesion or any other contraindications to tDCS [55]. The study was approved by the University's ethic committee and participants signed an informed

consent before commencing the study. They received course credits for participation. Complete datasets were obtained from 42 participants and were used for further statistical analysis, only one participant had to be excluded due to missing data (questionnaires). Average age was $M = 22.02$ years ($SD = 4.25$, Range: 17–40) and average body mass index (BMI) was $M = 22.60 \text{ kg/m}^2$ ($SD = 3.09$, Range: 17.65–33.44). Based on the guidelines of the World Health Organization [71], 4 women (9.52%) were underweight (BMI < 18.50 kg/m^2), 31 (73.80%) had normal weight (BMI = 18.50–24.99 kg/m^2), 4 (9.52%) were overweight (BMI = 25.00–29.99 kg/m^2) and 2 (4.76%) were obese (BMI > 30.00 kg/m^2).

2.2. Experimental design

The study applied a within-subject, crossover design, in which participants received two types of tDCS-protocols (active, sham) during separate dates of laboratory assessment. A one-week intersession-interval was used to avoid potential carry-over effects of the stimulation. Order of the stimulation condition was counterbalanced across participants. Participants and experimenters (except one external investigator who applied tDCS) were blinded to the stimulation condition.

2.3. Stimulus material

To avoid potential habituation effects, two different sets of food stimuli (Set A, Set B; cf. Table 1 in the appendix) were used at the laboratory sessions (one at each session), with order counterbalanced across sessions. Each set consisted of 18 food stimuli, taken from a database of standardized food images (food-pics; [3,4]). Sets were made up of nine high caloric (sweet foods such as chocolate and savory foods such as pizza) and nine low caloric food stimuli (fruits such as banana and vegetables such as carrots). Pairs of food images were presented during the food choice task, single images were rated in the rating task and corresponding foods were available during the taste test.

2.4. Questionnaires

2.4.1. Hunger

Participants rated their current feeling of hunger on a visual analogue scale ranging from 0 (*no feeling at all*) to 100 (*very strong*). A second item asked participants to indicate how much time had passed since their last meal (in hours and minutes).

2.4.2. Barratt Impulsiveness Scale – short form (BIS-15)

Trait impulsivity was measured with the German version [50] of the BIS-15 [63], which is a short form of the 11th version of the Barratt Impulsiveness Scale (BIS-11; [59]). The scale has 15 items. In addition to a total score, three subscales scores can be calculated representing attentional (e.g., "I am restless at lectures or talks."), motor (e.g., "I buy things on impulse.") and non-planning (e.g., "I plan tasks carefully." [inverted]) impulsivity. Response categories range from 1 (*never/rarely*) to 4 (*almost always/always*). Thus, total scores can range between 15 and 60. In the current study, internal consistency of the total scale was $\alpha = 0.84$ and was $\alpha = 0.67$ (attentional impulsivity), $\alpha = 0.71$ (motor impulsivity), and $\alpha = 0.84$ (non-planning impulsivity) for the subscales.

2.4.3. Food Cravings Questionnaire – State (FCQ-S)

Momentary food craving was measured with a modified version of the German version of the Food Cravings Questionnaire-State [9,46]. The scale originally has 15 items, but a shortened 9-item version was used in the present study as participants completed the scale multiple times. Specifically, this modified version omitted items assessing anticipated affective states (positive and negative reinforcement) that may result from eating as items related to the current craving

experience and anticipated consumption were deemed more relevant for the aims of the current study. Thus, only items assessing a desire to eat (e.g., "I have an intense desire to eat [one or more specific foods].")," lack of control over consumption (e.g., "If I had [one or more specific foods] to eat, I could not stop eating it."), and hunger (e.g., "I am hungry.") were retained. Response categories range from 1 (*strongly disagree*) to 5 (*strongly agree*). Thus, total scores can range between 9 and 45. In the current study, internal consistencies ranged from $\alpha = 0.82$ to $\alpha = 0.89$ in the stimulation condition and $\alpha = 0.87$ to $\alpha = 0.90$ in the sham condition for the total scale.

2.5. Food choice task

Participants started the food choice task after having been instructed that the most frequently chosen foods would be available in the following taste test. For each trial, participants chose between two food pictures, which either consisted of two high caloric ("high/high"), two low caloric ("low/low"), or of a high and low caloric ("high/low") food. Participants completed two practice blocks (12 trials each), before completing four test blocks, each consisting of 54 choices (18 high/high, 18 low/low, 18 high/low). Trials were presented in randomized order, resulting in a total of 216 unique choice trials (duration 20 min). Note that the high/high and low/low condition were created to guarantee that enough high and low caloric foods have been selected by the participant for the taste test.

2.6. Procedure

Prior to the laboratory sessions (Fig. 1), participants completed questionnaires on sociodemographic and health-related data, the BIS-15, and others online.[1] To keep hunger comparable across participants, they were instructed to abstain from eating for at least three hours prior to laboratory assessment. After arrival at the laboratory between 2:00 and 4:00 p.m., participants read and signed informed consent and their height and weight were measured. Participants then rated their current hunger and completed the FCQ-S for the first time. The tDCS-electrodes were placed on their scalp and the device was switched on by an external investigator. During the stimulation, we used a computer-based process tracing method [16] to record the continuous movement trajectories of the computer mouse in a food choice task (for further information about the food choice task, see next section 'Food Choice Task').

After the food choice task, participants rated all food pictures on visual analogue scales according to their general liking ("How tasty is this food for you in general?") and desire to eat ("How strong is your desire to eat this food right now?"), anchored with 0 ('not at all') and 100 ('very tasty/strong'). After these rating tasks, the tDCS device was turned off and participants completed the FCQ-S for the second time. Subsequently, participants were offered generous amounts of the five high caloric and five low caloric foods that they had chosen most frequently during the high/high and low/low condition of the food choice task. They were instructed to taste as much as they liked and to rate the palatability of the tasted foods. Participants were left alone for 10 min. Finally, participants completed the FCQ-S for the third time, concluding one laboratory session. After participants had left, the remaining food was weighted to the nearest gram. Finally, participants were debriefed and compensated with course credits for their participation.

Note that the picture represents a typical food choice trial and start button, mouse cursor, screen size and food pictures are not true to scale. FCQ-S 1, FCQ-S 2, and FCQ-S 3 indicate the three times that participants completed the modified Food Cravings Questionnaire-State.

2.7. Transcranial direct current stimulation (tDCS)

Direct current was applied using a DC-Stimulator Plus device (NeuroConn GmbH, Ilmenau, Germany) with a pair of rubber electrodes (5 × 7 cm) covered by sponge pads soaked in a sterile solution of 0.9% sodium chloride. Impedances were kept below 50 kΩ. Participants received two types of stimulation protocols targeting the dlPFC. A third person set the device, unbeknownst to experimenter and subject, counterbalanced to either active stimulation or sham stimulation.

Active stimulation consisted of anodal stimulation of the right dlPFC and cathodal stimulation of the left dlPFC. The anode electrode was placed on the scalp over F4 and the cathode electrode over F3 (according to the international EEG 10/20 system; [36]). Both electrode positions were marked on the scalp of the participant using a fitting EEG cap. For active stimulation the current was ramped up for 15 s until it reached a constant of 1 mA, after which participants were stimulated for 20 min followed by a 15 s fade-out. The stimulation intensity of 1 mA has been chosen to guarantee successful assessor and subject blinding [58]. Both the current intensity and duration were in line with similar protocols that have been used safely in previous studies with healthy participants [6].

Sham stimulation involved the same electrode placement and procedures as the active condition; however, the device automatically turned off after 15 s of active stimulation. The sham protocol ensures comparable initial 'itching sensations' that usually accompany the start of the stimulation and has been shown to be barely distinguishable from active stimulation [18].

At the end of the second laboratory session, successful blinding to the stimulation condition was assessed by asking participants (in form of a questionnaire) whether they believe that there has been a placebo stimulation in any of the two sessions and if they felt a difference, they were asked to indicate which session they would assume to be the placebo session (the response options included: first session, second session or both sessions).

2.8. Data analysis

TDCS effects on momentary food craving (FCQ-S) were evaluated by a 2 (tDCS Condition: active, sham) × 3 (Measurement: 1, 2, 3) repeated measures analysis of covariance (ANCOVA) with impulsivity (BIS-15 total score, mean centered) as covariate. TDCS effects on desire to eat ratings, food choice (number of choice) and mouse tracking measures - reaction time, initiation time (time until the mouse movement has been initiated by the participant) and the area under the curve (for additional information about these measures, see: [16]) - were evaluated by a 2 (tDCS Condition: active, sham) × 2 (Caloric density: low caloric, high caloric) ANCOVAs with impulsivity as covariate. Effects on calorie intake in the taste test were tested with a one-way ANCOVA with the within-subjects factor tDCS condition (active, sham) and impulsivity as covariate.

3. Results

3.1. Manipulation checks

3.1.1. tDCS blinding

Thirty participants[2] (75%) indicated that they felt no difference between the two tDCS conditions on the first question of a short questionnaire. Of the 10 who did, 7 guessed the tDCS conditions correctly on the second question ("Which session would you assume to

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[1] We also administered the Dutch Eating Behavior Questionnaire (DEBQ; [69]) and the Food Cravings Questionnaire-Trait-reduced [45].

[2] For this analysis, we used 40 participants, because data were missing for two participants.
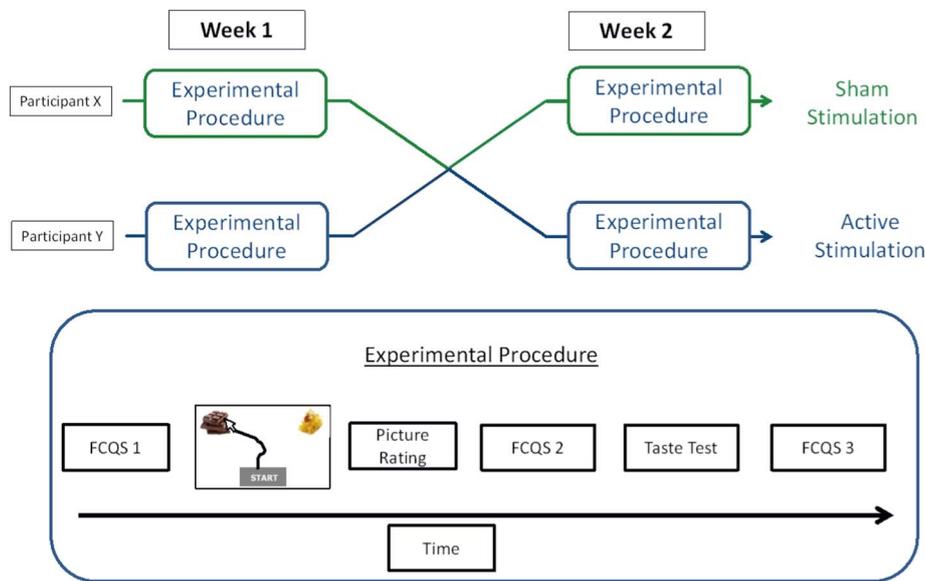
Fig. 1. Time schedule of laboratory sessions. Participants started with sham stimulation in week 1 and continued with active stimulation in week 2, or vice versa. This procedure was counterbalanced across participants. The experimental procedure depicts the time course of one laboratory session.

be the placebo session?"). However, analyses with and without these seven participants did not affect the results, which is why we continued with the full sample.

3.1.2. Hunger ratings

A Wilcoxon Signed-ranks test indicated that initial hunger ratings did not differ between the active tDCS laboratory session ($M = 40.60$, $Mdn = 39.50$, $SD = 24.53$) and the sham tDCS laboratory session ($M = 43.19$, $Mdn = 45.50$, $SD = 24.28$), $Z = -0.57$, $p = 0.572$.

3.2. Effects of tDCS and impulsivity

3.2.1. Momentary food craving (FCQ-S)

There were no main effects or interactions involving tDCS condition or impulsivity on momentary food craving, all $Fs \leq 1.194$, $ps \geq 0.281$. A significant main effect of measurement, $F(1, 40) = 57.512$, $p < 0.001$, $\eta_p^2 = 0.588$, indicated increased current food craving after the food choice task, $t(41) = 9.74$, $p < 0.001$, and decreased current food craving after the taste test, $t(41) = -5.01$, $p < 0.001$, suggesting successful craving induction (Fig. 2).

3.2.2. Desire to eat ratings

No significant effects involving impulsivity, tDCS condition, or type of foods were found, all $Fs \leq 1.31$, $ps \geq 0.260$ (for detailed description of means and standard deviations, see Table 3 in the appendix).

3.2.3. Food choices, reaction times and process tracing measures

No significant effects involving impulsivity or tDCS condition on number of choices for high caloric foods were found in the high/low condition, all $Fs \leq 2.79$ and $ps \geq 0.103$ (means and standard deviations in Table 1 in the appendix). Furthermore, we found no significant effects involving the caloric density of the selected food or tDCS condition for reaction times in the high/low condition, all $Fs \leq 0.570$ and $ps \geq 0.455$ (means and standard deviations in Table 2 in the appendix). Similarly, the analyses of the initiation time and area under the curve did not reveal significant main effects of stimulation or interactions with impulsivity, all $Fs \leq 1.587$ and $ps \geq 0.215$.

3.2.4. Calorie intake

Mean calorie intake in the taste test was $M = 586.22$ kcal ($SD = 236.50$). There was no significant main effect of tDCS condition ($F(1, 40) = 0.102$, $p = 0.751$, $\eta_p^2 = 0.003$). The two-way interaction
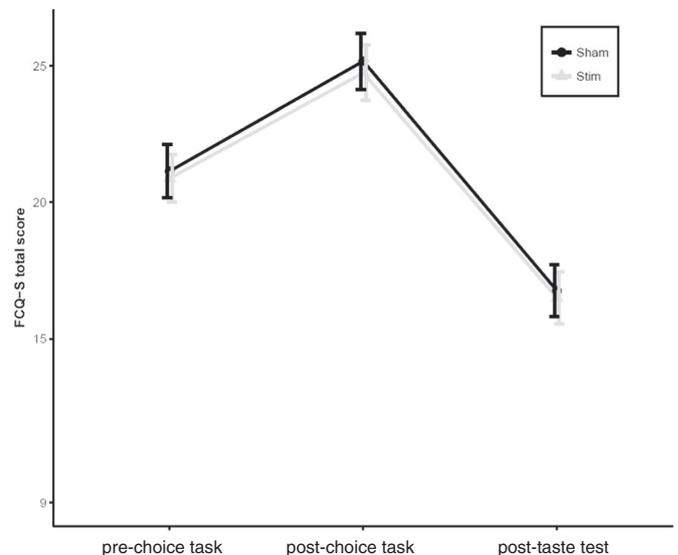

Fig. 2. Momentary food craving indexed by total scores of the modified Food Cravings Questionnaire – State (FCQ-S) for each measurement point as a function of tDCS condition (Stimulation & Sham).

between tDCS condition and impulsivity was not significant, $F(1, 40) = 0.071$, $p = 0.791$, $\eta p^2 = 0.002$. However, there was a significant main effect for the covariate impulsivity, $F(1, 40) = 8.203$, $p = 0.007$, $\eta p^2 = 0.170$. Higher impulsivity was related to higher calorie intake in the taste test, $r(42) = 0.413$, $p = 0.007$ (Fig. 3). Examining this relationship separately for the three BIS-15 subscales revealed that only the non-planning impulsivity subscale was positively correlated with calorie intake, $r(42) = 0.471$, $p = 0.002$. Attentional and motor impulsivity were positively, but not significantly, correlated with calorie intake, both $rs(42) \leq 0.260$, $p \geq 0.096$.

4. Discussion

The aim of the present study was to investigate effects of tDCS on a number of appetitive behaviors including food choice and intake in the laboratory. Trait impulsivity was considered as predictor of appetitive behaviors and as a potential moderator of tDCS effects. Previous research suggests that tDCS can be an effective way of reducing food
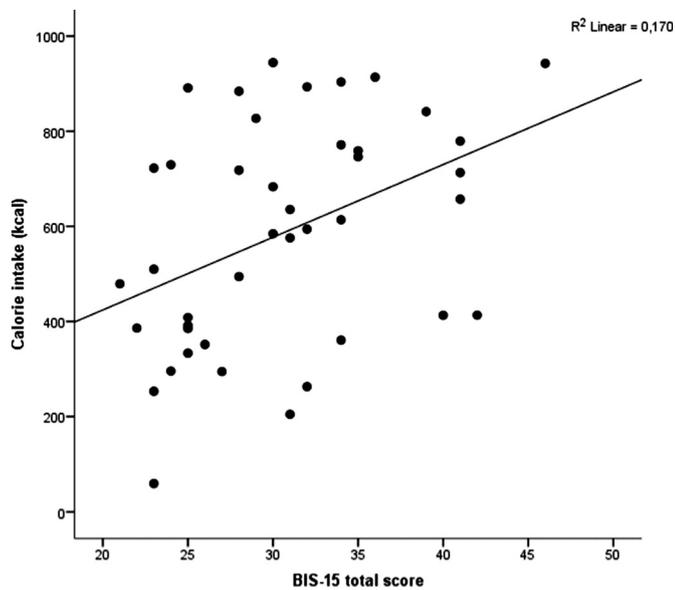
Fig. 3. Relationship between impulsivity (total scores of the Barratt Impulsiveness Scale-short form, BIS-15) and total calorie intake (kcal) in the taste test.

craving [34] and actual food intake (e.g., [17]) by stimulating brain areas involved in response inhibition, such as the dlPFC [10]. However, the present study found no main effects of active tDCS compared to sham tDCS on food craving, desire to eat ratings, food choice (including process tracing measures and reaction times) and calorie intake (*stimulation main effects*). While this contrasts with previous food craving-related studies, it is consistent with two recent meta-analyses that question the effectiveness of tDCS in healthy individuals for modulating cognition and the performance in a wide range of tasks [30,31]. As the current study used a sham-controlled, double-blinded within participant stimulation protocol [18] with adequate sample size (i.e., beta is 0.80 assuming a moderate effect size) and analyses suggested that subject blinding was overall successful, it is unlikely that results can be explained by biased assessment or expectancy effects. Also, possible confounding factors such as current hunger can be ruled out, as there was no difference between the two tDCS sessions. Moreover, state food craving was successfully induced, validating the laboratory task and the sensitivity of measurements.

One possible explanation for the null effect of tDCS stimulation could be sample characteristics. Previous studies either only recruited participants with frequent food cravings [17,20,38], or specific medical conditions associated with overeating [5] while the current sample was not preselected regarding such variables. Another possible explanation could be that the current study used a lower current intensity (1 mA) compared to previous studies, which mostly used 2 mA (e.g., [17]). However, Jauch-Chara et al. [37] also found tDCS effects on calorie intake and appetite scores for 1 mA [37] with very similar stimulation conditions (20 min of anodal stimulation of 1 mA) and 1 mA is a commonly used intensity in other research as well [6]. Importantly, a recent meta-analysis concluded that assessor blinding can be inadequate at intensities of 2 mA [58], raising the possibility that demand effects might have contributed to some of the previous, positive findings. In fact, blinding data where not uniformly reported or if so, indicated a relatively high number of 'unblinded' participants, which is why the present study opted for a lower intensity (1 mA). Still, stimulation intensity is a critical parameter on which tDCS-induced excitability modulation depends upon [56], calling for a systematic investigation of intensity level (1 vs. 2 mA) on food craving under rigorous control of condition blinding. Moreover, there are many sources of inter-subject variability [29] such as hair thickness, skull thickness, subcutaneous fat levels, cerebrospinal fluid density and cortical surface topography, which studies usually do not account for.

Another aim of the present study was to investigate how trait impulsivity and its various facets are related to food choice and intake (*impulsivity main effect*). The finding that higher impulsivity was associated with higher calorie intake in the taste test is in line with previous laboratory studies [22], implicating that impulsive people are more susceptible to overeating. It is also in line with studies showing that higher impulsivity is associated with a preference to consume energy dense, unhealthy foods [19,26]. However, contrary to our expectations, state food craving, desire to eat ratings, and food choice were unrelated to impulsivity, suggesting a differentiated response profile of impulsivity across dependent variables.

Examining associations between calorie intake and specific impulsivity facets in the current study revealed that a higher non-planning impulsivity in particular was associated with higher calorie intake. It has been suggested previously that particularly attentional and motor impulsivity (as assessed with the BIS-15), but not non-planning impulsivity, are associated to self-report measures that are related to overeating [43]. However, non-planning impulsivity related to striatal brain activation during high versus low caloric food choices [66] and attentional bias toward high versus low caloric food pictures [49] in experimental studies. Thus, it appears that while non-planning impulsivity may be inconsistently associated with self-reported eating styles and body weight [43,44], it may relate stronger to more direct measures of food cue reactivity such as higher reward-related brain activation or biased attentional processes [49,66]. Such heightened cue reactivity in combination with a lack of future orientation or forethought could result in a preference for immediate gratification of consuming high caloric palatable food at the costs of long-term health goals (e.g., keeping a healthy diet).

Unexpectedly, however, impulsivity did not interact with tDCS condition for any of the dependent variables (*moderation analysis impulsivity*). Research on this moderation is equivocal: For example, Kekic et al. [38] found stronger tDCS effects on momentary food craving in individuals with lower impulsivity than individuals with higher impulsivity. Whereas this study in a small sample (N = 17) used a behavioral task to examine impulsivity (i.e., delay discounting task as a measure for state impulsivity), we assessed impulsivity as a stable personality trait [47]. Clearly, more research on the effects of tDCS in relation to state-level and trait-level impulsivity is needed.

The following limitations apply: Generalization of the current findings is limited to unselected, predominantly healthy weight women. Given differences in, for example, impulsivity and food craving between women and men and between healthy and clinical (e.g., obese and/or eating disordered) samples, it may be that results would be different in such individuals. Furthermore, future studies may benefit from measuring state impulsivity with behavioral measures in addition to trait impulsivity (see [23]; e.g., the Stop Signal Task: [24]), given the multidimensional nature of the construct. Our results do not preclude the possibility that tDCS modulates state impulsivity indices such as response inhibition [33], risk taking [12,13] or that it affects appetitive behaviors as a function of state impulsivity (i.e., [38]). Furthermore, while our food decision task is–in principle–very sensitive to conflictive decisions (by yielding several process tracing measures), it was not optimized to induce a conflict between calorie density and palatability (i.e., where participants had to overrule their palatability preference for a low caloric option). Other researchers have optimized food decision tasks for the examination of such conflicts in weight-concerned individuals (e.g., [67]). Thus, inhibitory effects and associated tDCS stimulation effects might have been clearer when preselecting individuals on restrained eating and/or individually optimizing choice trials for self-regulation conflicts.

To conclude, contrary to previous research, single-session tDCS stimulation at 1 mA of the right dLPFC was not effective in reducing food craving, high caloric food choice and calorie intake in unselected, predominantly healthy weight women. Power in the present study was adequate, so future studies might focus on repeated sessions or different

intensities, in populations like dieters, which might be needed to determine the utility of tDCS as an intervention for modifying eating behavior. Further, the current study found support for the assumption that general impulsivity is related to overeating and may therefore be a risk factor for weight gain and obesity in the long run. Additionally, facets of impulsivity seem to play a differential role in overeating and should therefore be thoroughly investigated in future studies.

Appendix

Table 1
List of used high and low caloric pictures retrieved from the food. pics-database [3,4].

Set A	0022, 0157, 0167, 0169, 0183, 0184, 0192, 0198, 0200, 0268, 0341, 0380, 0430, 0515, 0520, 0531, 0535, 0555
Set B	0032, 0065, 0080, 0117, 0161, 0176, 0194, 0197, 0202, 0258, 0267, 0281, 0296, 0298, 0341, 0424, 0454, 0519

Table 2
Desire to eat ratings for high and low caloric foods and food choice in the high/low condition of the food choice task as a function of tDCS condition.

	tDCS active				tDCS sham			
	High caloric		Low caloric		High caloric		Low caloric	
Variable	M	SD	M	SD	M	SD	M	SD
Desire to eat	51.63	12.61	49.45	14.32	50.05	16.45	47.87	16.36
Number of choices	39.40	14.28	32.60	14.28	36.90	14.44	35.10	14.44

Table 3
Reaction times for high and low caloric foods in the high/low condition of the food choice task.

	tDCS active				tDCS sham			
	High caloric		Low caloric		High caloric		Low caloric	
Variable	M	SD	M	SD	M	SD	M	SD
Reaction time (ms)	1335.32	223.22	1342.39	196.87	1334.66	220.45	1348.05	198.41

References

[1] L. Batterink, S. Yokum, E. Stice, Body mass correlates inversely with inhibitory control in response to food among adolescent girls: an fMRI study, NeuroImage 52 (4) (2010) 1696–1703, http://dx.doi.org/10.1016/j.neuroimage.2010.05.059.

[2] J.D. Beaver, A.D. Lawrence, J. van Ditzhuijzen, M.H. Davis, A. Woods, A.J. Calder, Individual differences in reward drive predict neural responses to images of food, J. Neurosci. 26 (19) (2006) 5160–5166, http://dx.doi.org/10.1523/jneurosci.0350-06.2006.

[3] J. Blechert, A. Meule, N.A. Busch, K. Ohla, Food-pics: an image database for experimental research on eating and appetite, Front. Psychol. 5 (617) (2014) 1–10.

[4] J. Blechert, A. Meule, N.A. Busch, K. Ohla, Food-pics: an image database for experimental research on eating and appetite, Front. Psychol. 5 (2014) 617, http://dx.doi.org/10.3389/fpsyg.2014.00617.

[5] G.L. Bravo, A.B. Poje, I. Perissinotti, B.F. Marcondes, M.F. Villamar, A.M. Manzardo, ... M.G. Butler, Transcranial direct current stimulation reduces food-craving and measures of hyperphagia behavior in participants with Prader-Willi syndrome, Am. J. Med. Genet. B 171 (2) (2016) 266–275, http://dx.doi.org/10.1002/ajmg.b.32401.

[6] A.R. Brunoni, M.A. Nitsche, N. Bolognini, M. Bikson, T. Wagner, L. Merabet, ... F. Fregni, Clinical research with transcranial direct current stimulation (tDCS): challenges and future directions, Brain Stimulation 5 (3) (2012) 175–195, http://dx.doi.org/10.1016/j.brs.2011.03.002.

[7] E.E. Burgess, M.D. Sylvester, K.E. Morse, F.R. Amthor, S. Mrug, K.L. Lokken, ... M.M. Boggiano, Effects of transcranial direct current stimulation (tDCS) on binge-eating disorder, Int. J. Eat. Disord. (2016), http://dx.doi.org/10.1002/eat.22554.

[8] A. Cepeda-Benito, M.C. Fernandez, S. Moreno, Relationship of gender and eating disorder symptoms to reported cravings for food: construct validation of state and trait craving questionnaires in Spanish, Appetite 40 (1) (2003) 47–54, http://dx.doi.org/10.1016/s0195-6663(02)00145-9.

[9] A. Cepeda-Benito, D.H. Gleaves, T.L. Williams, S.A. Erath, The development and validation of the state and trait food-cravings questionnaires, Behav. Ther. 31 (1) (2001) 151–173.

[10] C.D. Chambers, H. Garavan, M.A. Bellgrove, Insights into the neural basis of response inhibition from cognitive and clinical neuroscience, Neurosci. Biobehav. Rev. 33 (5) (2009) 631–646.

[11] S. Churchill, D.C. Jessop, Reflective and non-reflective antecedents of health-related behaviour: exploring the relative contributions of impulsivity and implicit self-control to the prediction of dietary behaviour, Br. J. Health Psychol. 16 (2) (2011) 257–272, http://dx.doi.org/10.1348/135910710X498688.

[12] S. Fecteau, D. Knoch, F. Fregni, N. Sultani, P. Boggio, A. Pascual-Leone, Diminishing risk-taking behavior by modulating activity in the prefrontal cortex: a direct current stimulation study, J. Neurosci. 27 (46) (2007) 12500–12505, http://dx.doi.org/10.1523/JNEUROSCI.3283-07.2007.

[13] S. Fecteau, A. Pascual-Leone, D.H. Zald, P. Liguori, H. Theoret, P.S. Boggio, F. Fregni, Activation of prefrontal cortex by transcranial direct current stimulation reduces appetite for risk during ambiguous decision making, J. Neurosci. 27 (23) (2007) 6212–6218, http://dx.doi.org/10.1523/JNEUROSCI.0314-07.2007.

[14] K. Foerde, J.E. Steinglass, D. Shohamy, B.T. Walsh, Neural mechanisms supporting maladaptive food choices in anorexia nervosa, Nat. Neurosci. 18 (11) (2015) 1571–1573, http://dx.doi.org/10.1038/nn.4136.

[15] L.A. Francis, E.J. Susman, Self-regulation and rapid weight gain in children from age 3 to 12 years, Arch. Pediatr. Adolesc. Med. 163 (4) (2009) 297–302, http://dx.doi.org/10.1001/archpediatrics.2008.579.

[16] J.B. Freeman, N. Ambady, MouseTracker: software for studying real-time mental processing using a computer mouse-tracking method, Behav. Res. Methods 42 (1) (2010) 226–241, http://dx.doi.org/10.3758/BRM.42.1.226.

[17] F. Fregni, F. Orsati, W. Pedrosa, S. Fecteau, F.A. Tome, M.A. Nitsche, ... P.S. Boggio, Transcranial direct current stimulation of the prefrontal cortex modulates the desire for specific foods, Appetite 51 (1) (2008) 34–41, http://dx.doi.org/10.1016/j.appet.2007.09.016.

[18] P.C. Gandiga, F.C. Hummel, L.G. Cohen, Transcranial DC stimulation (tDCS): a tool for double-blind sham-controlled clinical studies in brain stimulation, Clin. Neurophysiol. 117 (4) (2006) 845–850, http://dx.doi.org/10.1016/j.clinph.2005.12.003.

[19] K.B. Garza, M. Ding, J.K. Owensby, C.A. Zizza, Impulsivity and fast-food consumption: a cross-sectional study among working adults, J. Acad. Nutr. Diet. 116 (1) (2016) 61–68, http://dx.doi.org/10.1016/j.jand.2015.05.003.

[20] R.L. Goldman, J.J. Borckardt, H.A. Frohman, P.M. O'Neil, A. Madan, L.K. Campbell, ... M.S. George, Prefrontal cortex transcranial direct current stimulation (tDCS) temporarily reduces food cravings and increases the self-reported ability to resist food in adults with frequent food craving, Appetite 56 (3) (2011) 741–746, http://dx.doi.org/10.1016/j.appet.2011.02.013.

[21] M. Grall-Bronnec, A. Sauvaget, The use of repetitive transcranial magnetic stimulation for modulating craving and addictive behaviours: a critical literature review of efficacy, technical and methodological considerations, Neurosci. Biobehav. Rev. 47 (2014) 592–613.

[22] R. Guerrieri, C. Nederkoorn, A. Jansen, How impulsiveness and variety influence food intake in a sample of healthy women, Appetite 48 (1) (2007) 119–122, http://dx.doi.org/10.1016/j.appet.2006.06.004.

[23] R. Guerrieri, C. Nederkoorn, A. Jansen, The effect of an impulsive personality on overeating and obesity: current state of affairs, Psihologijske Teme 17 (2) (2008) 265–286.

[24] R. Guerrieri, C. Nederkoorn, M. Schrooten, C. Martijn, A. Jansen, Inducing impulsivity leads high and low restrained eaters into overeating, whereas current dieters stick to their diet, Appetite 53 (1) (2009) 93–100, http://dx.doi.org/10.1016/j.appet.2009.05.013.

[26] P.A. Hall, Executive control resources and frequency of fatty food consumption: findings from an age-stratified community sample, Health Psychol. 31 (2) (2012) 235.

[27] T.A. Hare, C.F. Camerer, A. Rangel, Self-control in decision-making involves modulation of the vmPFC valuation system, Science 324 (5927) (2009) 646–648, http://dx.doi.org/10.1126/science.1168450.

[28] J.O. Hill, H.R. Wyatt, G.W. Reed, J.C. Peters, Obesity and the environment: where do we go from here? Science 299 (5608) (2003) 853–855.

[29] J.C. Horvath, O. Carter, J.D. Forte, Transcranial direct current stimulation: five important issues we aren't discussing (but probably should be), Front. Syst. Neurosci. 8 (2) (2014).

[30] J.C. Horvath, J.D. Forte, O. Carter, Evidence that transcranial direct current stimulation (tDCS) generates little-to-no reliable neurophysiologic effect beyond MEP amplitude modulation in healthy human subjects: a systematic review, Neuropsychologia 66 (2015) 213–236, http://dx.doi.org/10.1016/j.neuropsychologia.2014.11.021.

[31] J.C. Horvath, J.D. Forte, O. Carter, Quantitative review finds no evidence of cognitive effects in healthy populations from single-session transcranial direct current stimulation (tDCS), Brain Stimulation 8 (3) (2015) 535–550, http://dx.doi.org/10.1016/j.brs.2015.01.400.

[32] R. Hou, K. Mogg, B.P. Bradley, R. Moss-Morris, R. Peveler, A. Roefs, External eating, impulsivity and attentional bias to food cues, Appetite 56 (2) (2011) 424–427, http://dx.doi.org/10.1016/j.appet.2011.01.019.

[33] L. Jacobson, D.C. Javitt, M. Lavidor, Activation of inhibition: diminishing impulsive behavior by direct current stimulation over the inferior frontal gyrus, J. Cogn. Neurosci. 23 (11) (2011) 3380–3387, http://dx.doi.org/10.1162/jocn_a_00020.

[34] J.M. Jansen, J.G. Daams, M.W. Koeter, D.J. Veltman, W. van den Brink, A.E. Goudriaan, Effects of non-invasive neurostimulation on craving: a meta-analysis, Neurosci. Biobehav. Rev. 37 (10) (2013) 2472–2480, http://dx.doi.org/10.1016/j.neubiorev.2013.07.009.

[35] A.J. Jasinska, M. Yasuda, C.F. Burant, N. Gregor, S. Khatri, M. Sweet, E.B. Falk, Impulsivity and inhibitory control deficits are associated with unhealthy eating in young adults, Appetite 59 (3) (2012) 738–747, http://dx.doi.org/10.1016/j.appet.2012.08.001.

[36] H.H. Jasper, The ten twenty electrode system of the international federation, Electroencephalogr. Clin. Neurophysiol. 10 (1958) 371–375.

[37] K. Jauch-Chara, A. Kistenmacher, N. Herzog, M. Schwarz, U. Schweiger, K.M. Oltmanns, Repetitive electric brain stimulation reduces food intake in humans, Am. J. Clin. Nutr. 100 (4) (2014) 1003–1009, http://dx.doi.org/10.3945/ajcn.113.075481.

[38] M. Kekic, J. McClelland, I. Campbell, S. Nestler, K. Rubia, A.S. David, U. Schmidt, The effects of prefrontal cortex transcranial direct current stimulation (tDCS) on food craving and temporal discounting in women with frequent food cravings, Appetite 78 (2014) 55–62, http://dx.doi.org/10.1016/j.appet.2014.03.010.

[39] K.L. Kerr, J.A. Avery, J.C. Barcalow, S.E. Moseman, J. Bodurka, P.S. Bellgowan, W.K. Simmons, Trait impulsivity is related to ventral ACC and amygdala activity during primary reward anticipation, Soc. Cogn. Affect. Neurosci. 10 (1) (2015) 36–42, http://dx.doi.org/10.1093/scan/nsu023.

[40] O.M. Lapenta, K.D. Sierve, E.C. de Macedo, F. Fregni, P.S. Boggio, Transcranial direct current stimulation modulates ERP-indexed inhibitory control and reduces food consumption, Appetite 83 (2014) 42–48, http://dx.doi.org/10.1016/j.appet.2014.08.005.

[41] J.L. Manwaring, L. Green, J. Myerson, M.J. Strube, D.E. Wilfley, Discounting of various types of rewards by women with and without binge eating disorder: evidence for general rather than specific differences, Psychol. Rec. 61 (4) (2011) 561–582.

[42] J. McClelland, M. Kekic, N. Bozhilova, S. Nestler, T. Dew, F. Van den Eynde, ... U. Schmidt, A randomised controlled trial of neuronavigated repetitive transcranial magnetic stimulation (rTMS) in anorexia nervosa, PLoS One 11 (3) (2016) e0148606, , http://dx.doi.org/10.1371/journal.pone.0148606.

[43] A. Meule, Impulsivity and overeating: a closer look at the subscales of the Barratt impulsiveness scale, Front. Psychol. 4 (2013) 177, http://dx.doi.org/10.3389/fpsyg.2013.00177.

[44] A. Meule, J. Blechert, Trait impulsivity and body mass index: a cross-sectional investigation in 3073 individuals reveals positive, but very small relationships, Health Psychol. Open 3 (2016) 1–6.

[45] A. Meule, T. Hermann, A. Kübler, A short version of the food cravings questionnaire-trait: the FCQ-T-reduced, Front. Psychol. 5 (2014) 190, http://dx.doi.org/10.3389/fpsyg.2014.00190.

[46] A. Meule, A. Lutz, C. Vögele, A. Kübler, Food cravings discriminate differentially between successful and unsuccessful dieters and non-dieters. Validation of the food cravings questionnaires in German, Appetite 58 (1) (2012) 88–97, http://dx.doi.org/10.1016/j.appet.2011.09.010.

[47] A. Meule, M. Mayerhofer, T. Gründel, J. Berker, C.B. Teran, P. Platte, Half-year retest-reliability of the Barratt impulsiveness scale–short form (BIS-15), SAGE Open 5 (1) (2015) 1–3.

[48] A. Meule, E.K. Papies, A. Kübler, Differentiating between successful and unsuccessful dieters. Validity and reliability of the perceived self-regulatory success in dieting scale, Appetite 58 (3) (2012) 822–826, http://dx.doi.org/10.1016/j.appet.2012.01.028.

[49] A. Meule, P. Platte, Attentional bias toward high-calorie food-cues and trait motor impulsivity interactively predict weight gain, Health Psychol. Open 3 (1) (2016) (2055102916649585).

[50] A. Meule, C. Vögele, A. Kübler, Psychometrische Evaluation der deutschen Barratt Impulsiveness Scale–Kurzversion (BIS-15), Diagnostica 57 (3) (2011) 126–133, http://dx.doi.org/10.1026/0012-1924/a000042.

[51] O. Mobbs, K. Iglesias, A. Golay, M. Van der Linden, Cognitive deficits in obese persons with and without binge eating disorder. Investigation using a mental flexibility task, Appetite 57 (2011) 263–271.

[52] F.G. Moeller, E.S. Barratt, D.M. Dougherty, J.M. Schmitz, A.C. Swann, Psychiatric aspects of impulsivity, Am. J. Psychiatry 158 (11) (2001) 1783–1793, http://dx.doi.org/10.1176/appi.ajp.158.11.1783.

[53] C. Nederkoorn, K. Houben, W. Hofmann, A. Roefs, A. Jansen, Control yourself or just eat what you like? Weight gain over a year is predicted by an interactive effect of response inhibition and implicit preference for snack foods, Health Psychol. 29 (2010) 389–393.

[54] M. Ng, T. Fleming, M. Robinson, B. Thomson, N. Graetz, C. Margono, ... S.F. Abera, Global, regional, and national prevalence of overweight and obesity in children and adults during 1980–2013: a systematic analysis for the Global Burden of Disease Study 2013, Lancet 384 (9945) (2014) 766–781.

[55] M.A. Nitsche, L.G. Cohen, E.M. Wassermann, A. Priori, N. Lang, A. Antal, ... F. Fregni, Transcranial direct current stimulation: state of the art 2008, Brain Stimulation 1 (3) (2008) 206–223.

[56] M.A. Nitsche, D. Liebetanz, A. Antal, N. Lang, F. Tergau, W. Paulus, Modulation of cortical excitability by weak direct current stimulation-technical, safety and functional aspects, Suppl. Clin. Neurophysiol. 56 (2003) 255–276.

[57] M.A. Nitsche, W. Paulus, Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation, J. Physiol. 527 (2000) 633–639.

[58] N.E. O'Connell, J. Cossar, L. Marston, B.M. Wand, D. Bunce, G.L. Moseley, L.H. De Souza, Rethinking clinical trials of transcranial direct current stimulation: participant and assessor blinding is inadequate at intensities of 2mA, PLoS One 7 (10) (2012) e47514, http://dx.doi.org/10.1371/journal.pone.0047514.

[59] J.H. Patton, M.S. Stanford, E.S. Barratt, Factor structure of the Barratt Impulsiveness Scale, J. Clin. Psychol. 51 (6) (1995) 768–774.

[60] A. Sauvaget, B. Trojak, S. Bulteau, S. Jiménez-Murcia, F. Fernández-Aranda, I. Wolz, ... M. Grall-Bronnec, Transcranial direct current stimulation (tDCS) in behavioral and food addiction: a systematic review of efficacy, technical, and methodological issues, Front. Neurosci. 9 (2015) 349, http://dx.doi.org/10.3389/fnins.2015.00349.

[61] M. Schulte-Mecklenbeck, M. Sohn, E. de Bellis, N. Martin, R. Hertwig, A lack of appetite for information and computation. Simple heuristics in food choice, Appetite 71 (2013) 242–251, http://dx.doi.org/10.1016/j.appet.2013.08.008.

[62] J. Sengupta, R. Zhou, Understanding impulsive eaters' choice behaviors: the motivational influences of regulatory focus, J. Mark. Res. 44 (2) (2007) 297–308.

[63] M. Spinella, Normative data and a short form of the Barratt Impulsiveness Scale, Int. J. Neurosci. 117 (3) (2007) 359–368, http://dx.doi.org/10.1080/00207450600588881.

[64] B.A. Swinburn, G. Sacks, K.D. Hall, K. McPherson, D.T. Finegood, M.L. Moodie, S.L. Gortmaker, The global obesity pandemic: shaped by global drivers and local environments, Lancet 378 (9793) (2011) 804–814, http://dx.doi.org/10.1016/s0140-6736(11)60813-1.

[65] I.H. Valdes, J.H. Steinberg, P.A. Narayana, L.A. Kramer, D.M. Dougherty, A.C. Swann, ... F.G. Moeller, Impulsivity and BOLD fMRI activation in MDMA users and healthy control subjects, Psychiatr. Res. Neuroimaging 147 (2006) 239–242.

[66] L.N. Van der Laan, M.E.A. Barendse, M.A. Viergever, P.A.M. Smeets, Subtypes of trait impulsivity differentially correlate with neural responses to food choices, Behav. Brain Res. 296 (2016) 442–450, http://dx.doi.org/10.1016/j.bbr.2015.09.026.

[67] L.N. van der Laan, D.T.D. de Ridder, L. Charbonnier, M.A. Viergever, P.A.M. Smeets, Sweet lies: neural, visual, and behavioral measures reveal a lack of self-control conflict during food choice in weight-concerned women, Front. Behav. Neurosci. 8 (184) (2014), http://dx.doi.org/10.3389/fnbeh.2014.00184.

[68] L.N. van der Laan, P.A.M. Smeets, You are what you eat: a neuroscience perspective on consumers' personality characteristics as determinants of eating behavior, Curr. Opin. Food Sci. 3 (2015) 11–18.

[69] T. van Strien, J.E.R. Frijters, G.P.A. Bergers, P.B. Defares, The Dutch Eating Behavior Questionnaire (DEBQ) for assessment of restrained, emotional, and external eating behavior, Int. J. Eat. Disord. 5 (1986) 295–315.

[70] A.K. Ventura, J. Worobey, Early influences on the development of food preferences, Curr. Biol. 23 (2013) 401–408.

[71] World Health Organization, Obesity: Preventing and Managing the Global Epidemic, World Health Organization, Geneva, 2000.