Research report

The effects of prefrontal cortex transcranial direct current stimulation (tDCS) on food craving and temporal discounting in women with frequent food cravings

Maria Kekic *, Jessica McClelland, Iain Campbell, Steffen Nestler, Katya Rubia, Anthony S. David, Ulrike Schmidt

Institute of Psychiatry, King’s College London, 16 De Crespigny Park, London SE5 8AF, UK

ARTICLE INFO

Article history:
Received 11 December 2013
Received in revised form 4 March 2014
Accepted 9 March 2014
Available online 20 March 2014

Keywords:
Transcranial direct current stimulation (tDCS)
Brain stimulation
Food cravings
Obesity
Eating disorders
Temporal discounting (TD)

ABSTRACT

Bulimia nervosa, binge-eating disorder, and some forms of obesity are characterised by compulsive over-eating that is often precipitated by food craving. Transcranial direct current stimulation (tDCS) has been used to suppress food cravings, but there is insufficient evidence to support its application in clinical practice. Furthermore, the potential moderating role of impulsivity has not been considered. This study used a randomised within-subjects crossover design to examine whether a 20-minute session of sham-controlled bilateral tDCS to the dorsolateral prefrontal cortex (anode right/cathode left) would transiently modify food cravings and temporal discounting (TD; a measure of choice impulsivity) in 17 healthy women with frequent food cravings. Whether the effects of tDCS on food craving were moderated by individual differences in TD behaviour was also explored. Participants were exposed to food and a film of people eating, and food cravings and TD were assessed before and after active and sham stimulation. Craving for sweet but not savoury foods was reduced following real tDCS. Participants that exhibited more reflective choice behaviour were more susceptible to the anti-craving effects of tDCS than those that displayed more impulsive choice behaviour. No differences were seen in TD or food consumption after real versus sham tDCS. These findings support the efficacy of tDCS in temporarily lowering food cravings and identify the moderating role of TD behaviour.

© 2014 Elsevier Ltd. All rights reserved.

Introduction

It has been proposed that certain foods – particularly those high in sugar – are addictive, and that obesity and eating disorders, such as bulimia nervosa (BN) and binge-eating disorder (BED), can be conceptualised as forms of addiction (Avena, Rada, & Hoebel, 2009). Food cravings (intense urges to consume particular foods) are thought to precipitate the compulsive overeating that characterises these conditions, and have been positively associated with binge-eating (Ng & Davis, 2013), daily calorie intake (Lafay et al., 2000), BMI (Franken & Muris, 2005), daytime sleep (Landis, Parker, & Dunbar, 2009), and dieting failure (Meule, Westenhöfer, & Kübler, 2011). There is also evidence that excessive craving for sweet foods is associated with drug and alcohol abuse (for a review see Pelchat, 2002).

Extensive behavioural and neurobiological data indicate many commonalities between food craving and drug craving (for a review see Pelchat, 2009). For instance, both lead to foraging and ingestion habits that persist and strengthen despite the threat of negative health and social consequences (Volkow & Wise, 2005) and, furthermore, cravings can predict both relapse to drug taking in abstinent substance users (Rosenberg, 2009) and weight regain after bariatric surgery in obese patients (Odom et al., 2010). The neurotransmitter systems implicated in food craving overlap substantially with those involved in drug craving; for example, exposure to both food and drug craving-provoking stimuli is associated with increased levels of reward circuitry dopaminergic activation in the brain (Blum, Liu, Shriner, & Gold, 2011). Food craving and drug craving are also mediated by shared functional neuroanatomy. Several brain regions appear to be involved (for a review see Tang, Fellows, Small, & Dagher, 2012), but most data suggest that the left, right, or bilateral dorsolateral prefrontal cortex (DLPFC; an area in the prefrontal cortex important for executive functioning) is activated in response to cues that induce both food (Gearhardt et al., 2011; Siep et al., 2009) and drug cravings (Bonson et al., 2002; Hayashi, Ko, Strafella, & Dagher, 2013; Maas et al., 1998). The level of cue-elicited prefrontal activation can predict prospective food intake...
A growing number of studies have sought to directly manipulate DLPFC activation as a means of reducing cravings. Two non-invasive brain stimulation (NIBS) methods have been used, both of which are well-tolerated, have minimal side effects, and do not require surgical procedures. Repetitive transcranial magnetic stimulation (rTMS) employs an electromagnetic field generated by a figure-eight coil to suppress (low-frequency) or enhance (high-frequency) cortical excitability in a localised area of the brain (McClelland, Bozhilova, Campbell, & Schmidt, 2013a). Alternatively, transcranial direct current stimulation (tDCS) involves the delivery of a weak electrical current via two surface electrodes; anodal and cathodal tDCS cause excitatory and inhibitory effects on underlying cortical neurons, respectively (McClelland et al., 2013a).

Research has consistently shown that NIBS can reduce drug craving in laboratory settings; cue-provoked cravings for cocaine, alcohol, and nicotine have been transiently lowered with a single session of rTMS or tDCS to the left or right DLPFC (Boggio et al., 2008; Camprodon, Martinez-Raga, Alonso-Alonso, Shih, & Pascual-Leone, 2007; Fregni et al., 2008b; Li et al., 2013; Mishra, Nizamie, Das, & Preraharaj, 2010). Emerging evidence indicates that NIBS can also temporarily lower cravings for foods (for reviews see Jansen et al., 2013; McClelland et al., 2013a). In the earliest of these studies, Uher et al. (2005) showed that a single session of high-frequency rTMS to the left DLPFC suppressed cravings in healthy women with frequent food cravings. This finding was later replicated by two studies using bilateral DLPFC tDCS (anode right/cathode left), the former also showing a reduction in calories ingested following active versus sham stimulation (Fregni et al., 2008a; Goldman et al., 2011). The effects of prefrontal cortex modulation have also been investigated in a clinical sample; Van den Eynde et al. (2010) found that high-frequency rTMS to the left DLPFC lowered cue-induced food cravings in patients with a bulimic disorder.

Although the anti-craving effects recorded in these experiments were temporary (the effects of a single session of rTMS or tDCS are expected to last for up to two hours, depending on the parameters used; Nitsche & Paulus, 2001; Hoogendam, Ramakers, & Lazzaro, 2010), it is possible that NIBS delivered over extended periods of time could induce longer-lasting behavioural responses through changes in neurotransplantacity. Indeed, interventions comprising multiple sessions of NIBS have shown therapeutic potential for a range of conditions, including BN (Downar, Sankar, Giacobbe, Woodside, & Colton, 2012), anorexia nervosa (McClelland et al., 2013b), and substance use disorder (Politi, Fauci, Santoro, & Smeraldi, 2008). Moreover, rTMS is now an approved second-line treatment for major depressive disorder in the USA. Given that food cravings play a central role in obesity and some eating disorders, the potential for NIBS to enduringly suppress these cravings represents an exciting prospect.

Whilst the tendency to overeat or binge-eat can be influenced by food cravings, Davis, Levitan, Mouglia, Bewell, and Kennedy (2004) point out that “human overeating is not just a passive response to . . . powerful physiological drives; it is also about making choices” (p. 929). It is well-established that drug addicts have maladaptive decision-making capabilities (for a review see Dom, Sabbe, Hulsstijn, & van den Brink, 2005), and the same applies to compulsive overeaters. Specifically, obese people and patients with BED show steeper rates of temporal discounting (TD) (Davis, Patte, Curtis, & Reid, 2010; Weller, Cook, Avsar, & Cox, 2008) – an experimental proxy of aspects of impulsivity such as temporal foresight and delay of gratification. In the context of eating, these individuals struggle to defer food gratification in the interest of future health or aesthetics. Evidence shows that the capacity for self-control in reward-related decision-making tasks – including TD – depends crucially on DLPFC activity levels (Christakou, Brummer, & Rubia, 2011; Clark, Manes, Antuon, Sahakian, & Robbins, 2003; Hare, Camerer, & Rangel, 2009). Furthermore, reduced prefrontal reactivity during a TD task has been found to predict a greater rate of weight gain in obesity (Kishinevsky et al., 2012). It is possible that NIBS could reduce overeating behaviours by simultaneously suppressing food cravings and improving intertemporal decision-making. Indeed, Figner et al. (2010) showed that low-frequency rTMS delivered to the left DLPFC altered the discounting of delayed rewards in healthy adults. Nevertheless, to our knowledge, the relationship between the DLPFC, food craving, and TD behaviour is yet to be explored.

This study investigated whether bilateral manipulation of the DLPFC with tDCS modulates food craving-related thoughts and behaviours in healthy women who experience frequent food cravings. tDCS was chosen because of its practical advantages over rTMS (Poreisz, Boros, Antal, & Paulus, 2007; Priori, Hallett, & Rothwell, 2005), and because its efficacy in lowering food cravings has been demonstrated in two non-clinical samples comparable to our own (Fregni et al., 2008a; Goldman et al., 2011). Unlike these studies, however, we also included a measure of choice impulsivity. The main aims were to establish whether: (1) one session of sham-controlled tDCS (anode over the right DLPFC and cathode over the left DLPFC) would temporarily reduce food cravings; (2) this session of tDCS would transiently alter TD behaviours; and (3) the effects of tDCS on food cravings are moderated by individual differences in intertemporal decision-making abilities. Based on Fregni et al.’s (2008a) finding, we also speculated that actual food consumption in a free-eating task might decrease following active versus sham stimulation.

Materials and methods

Participants

Healthy female volunteers who self-identified as having frequent food cravings (>1 per day, assessed by self-report questionnaire) aged 18-60 were recruited from the King’s College London (KCL) recruitment webpage. Respondents were screened by phone and were excluded if they: (a) smoked >10 cigarettes per day; (b) drank > the recommended daily alcohol intake (3–4 units for men and 2–3 units for women; National Health Service, 2013); (c) used illicit drugs; (d) had a current major psychiatric disorder; (e) had a past or current history of an eating disorder; (f) had any significant health problems in the previous 6 months; (g) had a personal or family history of seizures; (h) had a history of stroke; (i) had a history of head injury or neurosurgery; (j) had any implanted metal devices; (k) suffered from frequent or severe headaches; (l) were taking any medications associated with lowered seizure threshold; (m) were pregnant or sexually active and not using contraception; (n) were allergic to any of the foods presented in the study; or (o) gave any threshold answers in the Structured Clinical Interview for Diagnostic and Statistical Manual (DSM) Axis I Disorders (SCID-I; First, Spitzer, Gibbon, & Williams, 2002).

Twenty-eight women completed the telephone screen and 25 fulfilled all inclusion/exclusion criteria. Of these, 20 completed both study sessions – 4 withdrew before the first visit and 1 experienced skin irritation and so did not return for the second appointment. The data of three participants were excluded due to their responses in baseline assessments completed in the laboratory – 2 had clinically significant global scores (>4; Re, Reas, & Rosenvinge, 2012) on the Eating Disorder Examination Questionnaire (EDE-Q).
A 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree), yielding a global score and a score for each dimension.

Hormonal stress response (saliva sample)

To assess whether tDCS had an effect on the hypothalamus–pituitary–adrenal (HPA) axis stress response, we collected salivary cortisol samples. Participants chewed on a 3 × 1 cm inert polymer oral swab (Salivette®) for 1 min, which was then placed into a capped centrifuge tube. Samples were stored at −20°C – where they remain stable for up to 3 months (Garde & Hansen, 2005) – and were analysed for cortisol using competitive immunoassays (Salimetrics® salivary ELISA kits). Data indicate that cortisol measurement with Salivettes® is a reliable prediction method of total and calculated free serum cortisol levels (Poll et al., 2007).

Temporal Discounting (TD) task

Choice impulsivity was assessed with a computerised hypothetical monetary TD task, which measures the degree to which a reward is subjectively discounted in relation to its temporal delay (Rubia, Halari, Christakou, & Taylor, 2009). A monetary task was used because compulsive overeaters appear to have a general tendency to make impulsive choices, which is not specific to choices about food (Manwaring, Green, Myerson, Strube, & Wilfley, 2011). Participants chose between a smaller amount of money (between £0 and £100) available immediately, and a larger amount (always £100) available after 1 week, 1 month, 1 year, or 2 years (25 trials for each delay). The value of the immediate reward was adjusted in an algorithm based on previous choices; this narrowed the range of the immediate values offered until an amount was reached that the participant judged as equivalent to the fixed delayed reward (Richards, Zhang, Mitchell, & de Wit, 1999). This point of subjective equality is referred to as the indifference point. A hyperbolic decay function was fitted to the indifference point for each delay to describe the relationship between the subjective value of a reward as a function of the delay to its presentation. The mathematical expression of this relationship is \( V = A/(1 + kD) \), where \( V \) is the subjective value of a reward of amount \( A \), \( D \) is the delay to reward

Table 1

Baseline characteristics of participants.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Mean</th>
<th>SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>26.41</td>
<td>8.31</td>
<td>19.00–55.00</td>
</tr>
<tr>
<td>BMI</td>
<td>23.81</td>
<td>2.60</td>
<td>19.90–29.30</td>
</tr>
<tr>
<td>DASS–21 depression</td>
<td>3.88</td>
<td>4.33</td>
<td>0.00–14.00</td>
</tr>
<tr>
<td>DASS–21 anxiety</td>
<td>2.12</td>
<td>2.40</td>
<td>0.00–8.00</td>
</tr>
<tr>
<td>DASS–21 stress</td>
<td>7.18</td>
<td>4.53</td>
<td>0.00–18.00</td>
</tr>
<tr>
<td>Global EDE-Q</td>
<td>1.46</td>
<td>0.98</td>
<td>0.49–3.88</td>
</tr>
<tr>
<td>Global FCQ-T</td>
<td>118.47</td>
<td>18.46</td>
<td>91.00–151.00</td>
</tr>
<tr>
<td>Cravings per day</td>
<td>3.15</td>
<td>1.36</td>
<td>1.00–5.50</td>
</tr>
<tr>
<td>Baseline k-value</td>
<td>8.05</td>
<td>9.86</td>
<td>0.91–39.92</td>
</tr>
</tbody>
</table>

SD, standard deviation; BMI, body mass index; DASS–21, 21-item Depression, Anxiety and Stress Scale; EDE-Q, Eating Disorders Examination Questionnaire; FCQ-T, Food Craving Questionnaire-Trait.

Assessed with self-report demographic questionnaire (“How many food cravings do you experience per day?”).

This is a behavioural measure – used to induce and assess food cravings – which was developed and administered previously in our laboratory (Uher et al., 2005; Van den Eynde et al., 2010; Van den Eynde, Guillaume, Broadbent, Campbell, & Schmidt, 2013), and adapted for use in the current study. Two short films (<3 min each) of adults eating energy-dense foods (chocolates, crisps, nuts, and biscuits) were shown to participants consecutively, and the same foods were present in the room. After the films, participants rated their attitude towards food intake and their emotional state on a series of 10 cm continuous VASs measuring appearance, smell, taste, and urge to eat for each food separately, as well as hunger, general urge to eat, general urge to binge, stress, anxiety, tension, and mood. The primary outcome variable in the analyses (global FCT score) was computed by totalling the ratings on all VASs relating to food intake except for hunger. This is because food cravings tend to be hedonically driven and are unrelated to an individual’s physiological needs (Davis et al., 2010; Pelchat, Johnson, Chan, Valdez, & Ragland, 2004).

Food Craving Questionnaire-State (FCQ-S)

This is a self-report inventory used to assess food craving as a psychological state in response to specific situations, which was developed for use among average-weight adults (Cepeda-Benito et al., 2000). The instrument contains 15 items organised into 5 subscales. Responses are made on a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree), yielding a global score and a score for each dimension.

To assess whether tDCS had an effect on the hypothalamus–pituitary–adrenal (HPA) axis stress response, we collected salivary cortisol samples. Participants chewed on a 3 × 1 cm inert polymer oral swab (Salivette®) for 1 min, which was then placed into a capped centrifuge tube. Samples were stored at −20°C – where they remain stable for up to 3 months (Garde & Hansen, 2005) – and were analysed for cortisol using competitive immunoassays (Salimetrics® salivary ELISA kits). Data indicate that cortisol measurement with Salivettes® is a reliable prediction method of total and calculated free serum cortisol levels (Poll et al., 2007).

Temporal Discounting (TD) task

Choice impulsivity was assessed with a computerised hypothetical monetary TD task, which measures the degree to which a reward is subjectively discounted in relation to its temporal delay (Rubia, Halari, Christakou, & Taylor, 2009). A monetary task was used because compulsive overeaters appear to have a general tendency to make impulsive choices, which is not specific to choices about food (Manwaring, Green, Myerson, Strube, & Wilfley, 2011). Participants chose between a smaller amount of money (between £0 and £100) available immediately, and a larger amount (always £100) available after 1 week, 1 month, 1 year, or 2 years (25 trials for each delay). The value of the immediate reward was adjusted in an algorithm based on previous choices; this narrowed the range of the immediate values offered until an amount was reached that the participant judged as equivalent to the fixed delayed reward (Richards, Zhang, Mitchell, & de Wit, 1999). This point of subjective equality is referred to as the indifference point. A hyperbolic decay function was fitted to the indifference point for each delay to describe the relationship between the subjective value of a reward as a function of the delay to its presentation. The mathematical expression of this relationship is \( V = A/(1 + kD) \), where \( V \) is the subjective value of a reward of amount \( A \), \( D \) is the delay to reward
presentation, and $k$ is a constant characterising the individual’s rate of discounting (Rachlin, Raineri, & Cross, 1991). The value of $k$ is frequently used as the main dependent variable in the TD paradigm, and is considered an experimental proxy of aspects of impulsivity such as temporal foresight and delay of gratification. Participants with larger $k$-values show greater TD – for them rewards gained after a delay lose more subjective value.

Real transcranial direct current stimulation (tDCS)

A single 20-minute session of tDCS was delivered using a neuroCom® DC-STIMULATOR device at a constant current of 2 mA (with a 10-second fade in/out) using two 25 cm² surface sponge electrodes soaked in a sterile saline solution (0.9% sodium chloride). At least 50% of this transcranially applied current is expected to enter the brain through the skull (Nitsche et al., 2008). The anode and cathode were placed over the right (F4) and left (F3) DLPFC, respectively. The sites of interest were located using the International EEG 10-20 system. The tDCS parameters used have been shown to be safe in healthy individuals (Iyer et al., 2005) and the charge density was two magnitudes lower than the experimentally determined threshold estimate in rats (Liebetanz et al., 2009). tDCS is generally well-tolerated and is associated with relatively minor side effects; a mild tingling sensation is the most commonly reported adverse effect (Poreisz et al., 2007). We assessed tolerability via salivary cortisol and a 10 cm continuous VAS measuring discomfort during the procedure.

Sham transcranial direct current stimulation (tDCS)

The electrode placement for sham tDCS was the same as for active tDCS; however, the stimulation automatically turned off after 30 s. Participants therefore experienced the initial itching sensation but received no current for the rest of the 20-minute session. Research shows that this method for sham tDCS is reliable and cannot easily be distinguished from real tDCS by participants or investigators (Gandiga, Hummel, & Cohen, 2006). The validity of the sham treatment was assessed by asking participants to guess which session they thought was a placebo, and to rate their confidence in this guess on a 10 cm continuous VAS.

Free-eating task

To measure actual food consumption after real and sham tDCS, weights of foods presented in the FCT were recorded before and after each laboratory session. After the final post-tDCS measure, the experimenter left the room for 3 min and invited the participant to help themselves to any of the foods while they were gone. The percentage eaten was calculated for each food separately and for all foods together.

Results

Statistical analyses were performed using IBM® SPSS® software (Version 20). For variables with normally distributed data, the effects of active versus sham tDCS were evaluated using two-way 2 (stimulation: real vs. sham) × 2 (timepoint: pre-tDCS vs. post-tDCS) repeated measures ANOVAs, whereby a significant stimulation × timepoint interaction indicated a difference in the effect that real and sham tDCS had on pre-tDCS scores. Where data were not normally distributed, non-parametric alternatives were employed. All statistical tests were two-tailed and the level of significance was set at $\alpha = 0.05$.

Food cravings and tDCS

When compared with sham stimulation, real stimulation did not alter global FCT scores [$F(1, 16) = 0.74$, ns]. There was a significant stimulation × timepoint interaction for global FCQ-S score [$F(1, 16) = 5.02, P < .05$] in the opposite direction to that expected; pre-tDCS scores were lowered more by sham ($M = −11.32\%, SD = 21.12\%$) than by real stimulation ($M = −1.94\%, SD = 21.36\%$). However, this finding is largely attributable to scores on FCQ-S subscale 5 (craving as a physiological state) as the global FCQ-S interaction term was not significant when this subscale was excluded from the analysis [$F(1, 16) = 3.19$, ns].

Food cravings for specific food groups and tDCS

To examine the effect of tDCS on cravings for specific food groups, we analysed FCT ratings (appearance, smell, taste, urge to eat) for sweet (chocolate and biscuits) and savoury (crisps and nuts) foods separately. A significant stimulation × timepoint interaction was observed for sweet [$F(1, 16) = 4.59, P < .05$] but not savoury foods [$F(1, 16) = 2.20$, ns]. Cravings for sweet foods were reduced more by real ($M = −13.31\%, SD = 34.73\%$) than by sham tDCS ($M = −6.06\%, SD = 29.86\%$), whilst cravings for savoury foods were lowered by comparable amounts in both conditions (real: $M = −9.29\%, SD = 36.84\%$, sham: $M = −10.30\%, SD = 30.46\%$) (Fig. 1).

Temporal discounting and tDCS

Since $k$-values on the TD task were not normally distributed, the effect of tDCS on intertemporal choice behaviour was evaluated using paired-samples Wilcoxon signed-rank tests. Post-tDCS $k$-values did not differ significantly from pre-tDCS $k$-values following real [$z = −0.45$, ns] or sham stimulation [$z = −0.31$, ns].

Fig. 1. Mean percentage change in Food Challenge Task scores (appearance, smell, taste, urge to eat) for sweet and savoury foods in real and sham tDCS conditions. Error bars represent ± SE.
Interaction between temporal discounting, food cravings, and tDCS

To establish whether the effects of tDCS on food cravings were moderated by individual differences in intertemporal decision-making abilities, we performed the analyses with baseline k-value (calculated as the mean of the two pre-tDCS k-values) as a covariate. Results showed a significant stimulation × timepoint interaction for global FCT score \[ F(1, 15) = 4.82, P < .05 \]; after controlling for baseline k-value there was a sharper decrease in global FCT scores following real tDCS than following sham tDCS. In addition, the stimulation × timepoint interaction for global FCQ-S score was no longer significant \[ F(1, 15) = 0.18, ns \].

There was also a significant stimulation × timepoint × baseline k-value interaction for global FCT score \[ F(1, 15) = 5.12, P < .05 \] and global FCQ-S score \[ F(1, 15) = 5.60, P < .05 \]. Participants with lower baseline k-values – and greater intertemporal decision-making abilities – were more susceptible to the anti-craving effects of active tDCS. Conversely, baseline k-value did not moderate the effects that sham tDCS had on food cravings. To illustrate this graphically, we divided participants into two groups according on their baseline k-value; participants with baseline k-values in the first or second quartiles \( n = 9 \) were classified as showing low TD (more reflective choice behaviour) whilst those with baseline k-values in the third or fourth quartiles \( n = 8 \) were categorised as showing high TD (more impulsive choice behaviour) (Fig. 2).

Success of blinding procedure

Participants were not able to distinguish real stimulation from sham stimulation at a rate better than chance \( \chi^2(1) = 2.88, ns \). Furthermore, the mean confidence rating for this guess on a 10 cm continuous VAS was 5.04 \( (SD = 3.12, range = 0.0–9.7) \), indicating that participants were not particularly certain that their guess was accurate. The order in which participants received real and sham stimulation did not affect their ability to identify the placebo session \( [P = .29; \text{Fisher's exact test}] \).

Tolerability and safety of tDCS

One participant withdrew from the study after the first appointment due to skin irritation at the site of stimulation. Another participant reported developing a slight headache following active tDCS which subsided without treatment. Overall, the intervention was well-tolerated and participants reported experiencing minimal discomfort \( (10 \text{ cm VAS: } M = 2.64, SD = 2.51, \text{range} = 0–7.7) \). When compared with sham tDCS, real tDCS did not have any adverse effects on the HPA axis stress response \[ F(1, 15) = 0.29, \text{ns} \] and did not alter self-reported stress, anxiety, tension, or mood \[ Fs < 0.55, ps > .47 \].

Order effects

There was evidence of an order effect whereby, following real stimulation, participants allocated to the real/sham condition displayed a sharp decrease in global FCT scores whereas those in the sham/real condition showed a marginal increase in scores \[ F(1, 15) = 7.17, P < .05 \]. Participants who received real tDCS first \( n = 8 \) did not differ significantly from those who received sham tDCS first \( n = 9 \) in any baseline measures \[ Fs < 3.89, ps > .08 \].

Fig. 2. Mean pre- and post-tDCS global Food Challenge Task scores for participants showing high and low temporal discounting in real and sham tDCS conditions.
Discussion

The present study investigated the effects of a single session of sham-controlled tDCS (anode over the right DLPFC, cathode over the left DLPFC) on food cravings, intertemporal choice behaviour, and actual food consumption in healthy women with frequent food cravings. The key findings were that tDCS reduced cravings for sweet but not savoury foods, and that participants who exhibited more reflective choice behaviour were more susceptible to the anti-craving effects of tDCS than those who displayed more impulsive choice behaviour.

The observed decrease in craving for sweet foods is consistent with numerous accounts of prefrontal cortex tDCS transiently lowering food and drug cravings (Boggio et al., 2008; Fregni et al., 2008a, 2008b; Goldman et al., 2011), and provides evidence that food craving is associated with DLPFC activity. This brain region is thought to regulate cravings by integrating information relating to cues, cravings, motivation, and expectancy (McBride, Barrett, Kelly, Aw, & Dagher, 2006). By combining tRMS with functional magnetic resonance imaging (fMRI), Hayashi et al. (2013) formulated a two-stage model of cue-reactivity whereby the medial orbitofrontal cortex (mOFC) encodes the subjective value of the drug (or food) and the DLPFC incorporates intertemporal availability and cue information to modulate the presumed mOFC value signal.

The mechanisms by which DLPFC stimulation lowers cravings are unknown, although data suggest that reduced function in the right prefrontal cortex may lead to overeating (Alonzo-Alonso & Pascual-Leone, 2007). Interestingly, however, NIBS appears to suppress cravings even when the right DLPFC is inhibited and/or the left DLPFC is excited (Boggio et al., 2008; Fregni et al., 2008a, 2008b; Uher et al., 2005; Van den Eynde et al., 2010). It has therefore been proposed that state craving depends on a bilateral balance between left and right DLPFC activity and that any disruption to this balance will cause cravings to subside (Boggio et al., 2008). DLPFC modulation might also lead to craving inhibition by indirectly altering the activity level of the mOFC.

That tDCS suppressed cravings for sweet but not savoury foods is in approximate agreement with Goldman et al.’s (2011) findings, and provides an explanation as to why global FCQ-S and global FCT scores were not reduced by tDCS. It is possible that the mechanisms underlying cravings for sweet and savoury foods are different; several lines of evidence support this interpretation. Firstly, the concept of sweet food addiction is frequently likened to drug addiction (e.g. Avena, Rada, & Hoebel, 2008), whereas parallels have not been drawn between drug addiction and addiction to savoury foods. Secondly, chocolate contains several biologically active constituents – which are not found in savoury foods – that can cause psychological sensations comparable to those of other addictive substances (Brunisma & Taren, 1999). Thirdly, sweet foods generally contain higher sugar concentrations than savoury foods, and sugar is known to have addictive potential because it releases opioids and dopamine (Avena et al., 2008). Finally, ample data – including those in this study – indicate that cravings for sweet foods are stronger and more prevalent than cravings for savoury foods (Hill, 2007; Yanovski, 2003).

The present study demonstrates that inter-individual differences in intertemporal decision-making abilities moderate the anti-craving effects of prefrontal cortex tDCS. Specifically, participants who exhibited more impulsive choice behaviours showed a smaller reduction in cravings following active stimulation than those who displayed more reflective choice behaviours. This is unsurprising since individuals with a strong tendency to devalue delayed rewards are expected to hold particularly disinhibited attitudes towards food intake (Davis et al., 2010). Unlike Fgnier et al. (2010), we did not observe significant changes in TD following DLPFC modulation. It may be that an individual’s ability to delay gratification cannot be easily modified with NIBS; indeed, only one study has demonstrated otherwise and, moreover, the capacity for adaptive intertemporal decision-making is not a capricious psychological state but rather a stable personality trait (Davis et al., 2010).

In our study, real versus sham tDCS did not affect the amount of food consumed in the free-eating task. Although Fregni et al. (2008a) reported reduced caloric ingestion following active stimulation, Goldman et al. (2011) did not replicate this result. It is possible that the observed reduction in self-reported craving did not translate into an equipollent reduction in food consumption because the free-eating session lacked ecological validity; eating behaviours displayed in this task are unlikely to mirror those engaged in on a daily basis. Goldman et al. (2011) suggested instead performing “a natural observation of food consumption during a mealtime later in the day or the following day” (p. 745); however, the tDCS parameters used are not expected to have such a lasting effect. It might therefore prove more beneficial to revise the experimental free-eating task to improve its generalisability; for example, it could take place in a more natural setting and its length could be increased.

This study has some limitations; for example, we observed an order effect whereby real tDCS only reduced food cravings for participants who received real stimulation during their first session. One explanation for this draws on the finding that cue-induced craving for cigarettes was dramatically increased when people were told they could smoke immediately after testing (Hayashi et al., 2013). In our study, participants were not informed prior to testing that they would be given ad libitum access to a selection of foods; therefore, they would have only anticipated the free-eating task during their second visit, once they were familiarised with the experimental procedure. This anticipation might have potentiated cravings in the second session, making them less susceptible to modulation by tDCS. We did not ask participants to fast prior to their scheduled sessions. Although hunger is not a necessary prerequisite for food craving (Pelchat et al., 2004), similar studies have required that participants refrain from eating and drinking (except water) for several hours before testing (Goldman et al., 2011; Uher et al., 2005; Van den Eynde et al., 2010). Nevertheless, our results showed that baseline hunger was stable across conditions. We also did not collect data on menstrual phase despite evidence that it influences food craving (Davidsen, Vistisen, & Astrup, 2007); however, not all studies of NIBS and food craving have addressed this issue (Fregni et al., 2008a; Van den Eynde et al., 2010). In addition, we did not control for individual differences in IQ or income which may influence TD of monetary rewards (de Wit, Flory, Acheson, McCloskey, & Manuck, 2007; Green, Myers, Lichtman, Rosen, & Fry, 1996). A final limitation is that we did not include an anode left/cathode right tDCS condition, which would have helped to clarify whether there is a hemispheric laterality for food craving.

The present research has some important implications. Although the anti-craving effects observed here were presumably only temporary, it is possible that NIBS delivered over longer periods of time could elicit more sustained reductions in food craving. tDCS is an appealing technique because it is inexpensive, easy to administer, non-invasive, and painless. Future research should evaluate the therapeutic potential of tDCS for eliminating problematic overeating and binge-eating behaviours by analysing the effects of repeated DLPFC stimulation. The inter-individual differences we detected in a participant’s susceptibility to the anti-craving effects of stimulation suggest that, if developed into a treatment for compulsive overeating, tDCS might be less effective for patients with poorer intertemporal decision-making abilities. It may be possible to teach these individuals more adaptive strategies to prepare them for tDCS intervention.

In summary, our data contribute to the growing body of literature demonstrating that a single session of active tDCS to the DLPFC can temporarily suppress food craving. Our results support those
of Fregni et al. (2008a) and Goldman et al. (2011), and extend them by suggesting that tDCS has a stronger inhibitory effect on craving for sweet foods than on craving for savoury foods. We have also shown that individuals who exert more reflective choice behaviours are more susceptible to the anti-craving effects of tDCS than those who display more impulsive choice behaviours. The potential for DLPCF neuromodulation to transiently alter intertemporal choice behaviour was not supported here and warrants further investigation.

References


