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

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Abstract

This study examined whether a 20-min session of prefrontal transcranial direct current stimulation (tDCS) (anode over the right prefrontal cortex and cathode over the left prefrontal cortex) would reduce food cravings and increase the self-reported ability to resist foods in 19 healthy individuals who reported frequent food cravings. Participants viewed computerized images of food and used computerized visual analogue scales to rate food cravings and inability to resist foods before, during, and after receiving either real or sham tDCS. This study employed a randomized within-subject crossover design; participants received both real and sham tDCS and were blind to the condition. Food cravings ratings were reduced in both conditions, however, the percent change in cravings ratings from pre- to post-stimulation was significantly greater for real stimulation than for sham. The percent change in inability to resist food from pre- to post-stimulation also showed a greater decrease in the real condition than for sham. Post hoc analyses suggest that active prefrontal tDCS acutely and significantly decreased food cravings ratings for sweet foods and carbohydrates more than for sham tDCS. No significant differences were seen in the amount of food ingested between real and sham tDCS. These findings in healthy subjects indicate that tDCS is able to temporarily reduce food cravings and improve the self-reported ability to resist foods.

Introduction

According to the World Health Organization (2010) there are more than 300 million adults globally considered obese, and more than 1 billion overweight. Specifically, American society has been referred to as a “toxic” environment and has become “obesogenic,” characterized by increased food intake, exposure to high fat, high sugar foods and beverages, combined with a sedentary lifestyle and decreased exercise (Battle & Brownell, 1996; Horgen, Choate, & Brownell, 2001; Swinburn, Egger, & Raza, 1999; Wadden, Brownell, & Foster, 2002). Deterioration in the Western diet is hypothesized to contribute to the obesity epidemic. Results from the National Health and Nutrition Examination Survey (NHANES) (Centers for Disease Control and Prevention, 2006; Ogden et al., 2007) indicated that the United States prevalence of adult obesity has drastically increased in the past 20 years. The obesity epidemic has prompted scientists to examine food cravings as they may play a role in eating behaviors and weight gain (Delahanty, Meigs, Hayden, Williamson, & Nathan, 2002; Uher et al., 2004; Weingarten & Elston, 1990).
Craving has been defined as “an irresistible urge to consume” and has been associated with both overeating and substance abuse (Wang, Volkow, Thanos, & Fowler, 2004). It has been suggested and has been associated with both overeating and substance abuse (Wang et al., 2004). Previous research has identified many similarities that exist between binge eating and addiction (Budak & Thomas, 2009; Davis & Carter, 2009; Volkow & Wise, 2005). Just as cravings may predict relapse in addicted patients, some suggest that food cravings may predict relapse or weight regain in obese patients, including those who undergo bariatric surgery for weight loss (Anton, 1999; Budak & Thomas, 2009; Odom et al., 2009). Similarly, individuals that experience more frequent and intense food cravings are more likely to be overweight and/or develop eating-related disorders associated with excessive food intake (Gendall, Joyce, Sullivan, & Bulik, 1998).

Addictive drugs and addictive foods both activate brain circuitry involved in reward, motivation, and decision-making (Volkow, Fowler, Wang, & Swanson, 2004). Additionally, dopamine influences the brains reward circuitry and increased levels of dopamine is believed to reinforce the effects of addiction, either the addictive drug or the addictive food (Volkow & Wise, 2005). Previous positron emission tomography studies have shown both obese individuals and drug-addicted individuals to have lower dopamine D2 receptor levels (Wang et al., 2004). It has been suggested that these lower levels make them less sensitive to reward stimuli and thus more vulnerable to food, or drug intake, which is a way for the brain to compensate for the deficit. Furthermore, reductions in dopamine D2 receptors are associated with disruption in the prefrontal cortex, which is linked to compulsive behaviors and a decrease in impulse control (Volkow & Fowler, 2000).

There is emerging evidence implicating deficient prefrontal cortical inhibitory networks in over-eating and binge eating behaviors (Alonso-Alonso & Pascual-Leone, 2007). Brain imaging studies are beginning to elucidate the functional neuroanatomy of cravings (George et al., 2001; Myrick et al., 2004; Pelchat, Johnson, Chan, Valdez, & Ragland, 2004). While the role of the prefrontal cortex in regulating cravings remains somewhat unclear, frontal cortical areas appear to be involved in integrating incoming sensory information (i.e. sights, smells, and sounds) with affective/emotional information in the brain, and may be involved in regulating emotional reactions to various stimuli (Alexander, DeLong, & Strick, 1986; Lorenz, Minoshima, & Casey, 2003). Specifically, the dorsal lateral prefrontal cortex (DLPFC) may become activated when an individual is presented with cues that trigger reward memories associated with certain consumptive behaviors and induce cravings (Anton, 1999). One fMRI study found that when alcoholic subjects were presented with alcohol-related cues, there was greater activation in the left prefrontal cortex and anterior thalamus, compared to when they viewed non-alcohol cues (George et al., 2001). Other studies on bulimia and drug cravings have identified hyperactivity in the orbitofrontal cortex and anterior cingulate cortex associated with increases in cravings ratings (Goldstein & Volkow, 2002; Uher et al., 2004).

One of the first brain imaging studies of food cravings was published in 2004 by Pelchat and colleagues. Using fMRI, Pelchat et al. (2004) found that food cravings activate the same areas that are normally associated with drug cravings. In particular, they found activation of structures involved in memory, emotion, decision making, and habit learning. Very few studies have attempted to directly manipulate activation of brain structures that might be involved in food cravings. Uher et al. (2004) examined the effects of repetitive transcranial magnetic stimulation (rTMS) on food cravings in women with frequent cravings. They found that cravings remained stable during exposure to food with high frequency active rTMS, while they increased in the sham condition.

Transcranial direct current stimulation (tDCS), another minimally invasive brain stimulation technique, is capable of selectively activating or inhibiting specific cortical areas (Been, Ngo, Miller, & Fitzgerald, 2007). tDCS is an inexpensive, safe, and painless way to modulate brain activity that has not been shown to be associated with an increased risk of seizure. A low-amplitude direct electrical current (typically 1–2 mA) is applied via large sponge electrodes by a constant-current device to the human skull resulting in increased cortical activity underneath the anode and decreased activity under the cathode. Some of the behavioural effects of tDCS have been shown to last up to 90 min after a single 10–20 min stimulation session (Nitsche & Paulus, 2001; Poreisz, Boros, Antal, & Paulus, 2007) however, longer-term effects of tDCS may be achievable with repeated sessions (Loo et al., 2010; Mori et al., 2009; Vanneste et al., 2009). Previous research involving manipulation of brain activity using tDCS found that alcohol cravings decreased among individuals with alcohol dependence who received either left or right anodal stimulation of the DLPFC (Boggio et al., 2008). This finding, combined with prior functional neuroanatomical work, and research on the relation of food and drug cravings, suggests they share a common biologic mechanism (Pepino, Finkbeiner, & Mennella, 2009; Pepino and Mennella, 2007). Therefore, the prefrontal cortex may be a reasonable preliminary tDCS cortical target for potentially inhibiting food cravings.

To date, there has only been one published study examining the relationship between tDCS and food cravings. Fregni et al. (2008) found cravings to be reduced by active anode right/cathode left tDCS over the prefrontal cortex. The purpose of the current study was to test these findings for replication as well as to evaluate the effectiveness of tDCS in increasing participant-reported ability to resist foods. An additional measure of interest was to test the tDCS effects on an ecologically valid free-eating measure where participants were allowed to eat post-stimulation. Specifically, this study examined whether a single 20-min session of prefrontal tDCS (anode over the right prefrontal cortex and cathode over the left prefrontal cortex) delivered during and immediately following exposure to visual food stimuli would reduce food cravings and increase the ability to resist foods in healthy individuals who reported frequent food cravings. It was hypothesized that pre- to post-stimulation reductions in ratings of food cravings would be larger for real stimulation than for sham stimulation. Additionally, it was hypothesized that the change in reported ability to resist foods would increase more after real stimulation than after sham stimulation.

Methods

Participants

Healthy individuals aged 21–70 were recruited from the greater Charleston, South Carolina area via flyers and web broadcast advertisements. Participants were included if they had frequent food cravings and a Body Mass Index under 40. Participants were excluded if they: (a) were pregnant, (b) had a history of an eating disorder or depression, (c) were suicidal, (d) had implanted metal devices (e.g., pacemakers, metal plates, wires), (e) were on weight loss medication, (f) were currently participating in a weight loss program, (g) had a history of seizures, (h) had a family history of a seizure disorder, (i) were taking any medication associated with lowered seizure threshold, (j) had history of brain surgery or history of loss of consciousness >15 min, (k) had a history of an autoimmune or endocrine disorder, (l) were allergic to latex, or (m) had a peanut allergy (some of the food offered to participants may have contained peanuts). Eligibility was determined after the screening questionnaires (described below) were completed.
A total of 22 healthy individuals were initially enrolled in the study but only 19 met all inclusion/exclusion criteria and completed both study sessions. One participant did not return for the second appointment. One participant endorsed depressive symptoms as evidenced by their score on the CESD-10 (Andresen, Malmgren, Carter, & Patrick, 1994; Radloff, 1977) and the other participant did not endorse having regular problems with food cravings. The mean age of the 19 participants included in the analyses was 32.47 years (SD = 10.85). The majority of participants (78.9%) were between the ages of 21 and 45. Participants endorsed food cravings at least three times per week during the past month for at least one of the following food groups: (a) sweets; (b) fast food fats; (c) high fats; and (d) carbohydrates, as determined by the Food Craving Inventory (FCI; White, Whisenhunt, Williamson, Greenway, & Netemeyer, 2002). Participants mean weight was 82.02 kg (SD = 25.31), and the mean Body Mass Index (BMI) of the sample was 27.25 kg/m² (SD = 6.24); 26.3% had BMIs of 25–29.9 (overweight), and 31.6% had BMI’s greater than 30 (obese). The mean hours since participants last ate prior to laboratory visits was 8.25 h (SD = 3.50). The majority of participants were women (68.4%) and Caucasian (78.9%).

This study was approved by the Institutional Review Board of the Medical University of South Carolina. All participants provided written informed consent.

Screening

Interested participants called and were initially screened on the telephone. The research procedures, risks and benefits were also explained. If individuals appeared to meet the inclusion criteria they were scheduled for two sessions (each lasting approximately 90 min), within 48–72 h of each other. A 48–72 h intersession-interval was used to avoid the potential of any carry-over effects of stimulation since it is still unknown exactly how long the effects of tDCS can last. Formal questionnaires to verify that the participant met all inclusion/exclusion criteria were administered at the beginning of the first visit. If the participant was a pre-menopausal female, her sessions were scheduled during the luteal phase of her menstrual cycle, a time in the menstrual cycle where women experience more frequent food cravings (Davidsen, Vistisen, & Astrup, 2007). A random number generator developed by one of the investigators was used to determine if participants received real or sham tDCS at their first session. Participants were blind to condition (real or sham).

Procedure

This study employed a within-subject crossover design in which all participants received two different types of stimulation of the DLPFC utilizing tDCS: (1) active anode right/cathode left tDCS, and (2) sham tDCS with the same electrode placement. This electrode placement was chosen due to the findings of Fregni et al. (2008) in which food cravings were reduced after anode right/cathode left DLPFC stimulation and not changed after anode left/cathode right tDCS.

Although hunger is not necessary for food craving to occur, it was decided to manipulate food desire by asking all participants to not eat within 4 h of their scheduled session. Participants were reimbursed $50.00 for full participation. During the first appointment, informed consent was obtained and participants’ rights as research participants were explained. Participants then completed the Food Craving Inventory (FCI; White et al., 2002), and the Center for Epidemiological Studies Short Depression Scale (CESD-10; Andresen et al., 1994; Radloff, 1977). Their heights and weights were measured by a research assistant, and they completed a 24 h food recall.

After completing the initial questionnaires participants were seated at a computer where a series of standardized color food images from the International Affective Picture System (IAPS) were shown on the screen. The use of two-dimensional food pictures in craving studies is a widely used methodology and has been shown to produce unique cortical and sub cortical activation relative to pictures of non-food items (Killgore et al., 2003). Twenty-four images of foods (e.g., ice cream, cheese-burgers, pizza) were presented in random order using a custom-developed computer program. While viewing the food images, participants used a computerized visual analog scale (CVAS) to rate how much they “would like to eat each food right now if it were actually available” to them, how much they “liked the food”, and if the food were in front of them, how much they “would be able to resist tasting it”. The images were shown for as long as it took the participants to respond to the two questions presented. It took participants approximately 10 min to complete these ratings. The computer converted the visual ratings to numbers ranging from 0 to 100. The software for presenting the pictures and randomizing picture order was custom-developed using RealBasic3.5.5 on the Macintosh Platform and the program was run on a Macintosh G5 with a 24-in. LCD monitor running the Mac OS X operating system.

After viewing the food images, participants received 20 min of real or sham tDCS, using the parameters described below. During (after the first 10-min of stimulation) and after the full 20-min of real or sham tDCS, participants viewed the food images again (in randomized order) and rated their cravings and ability to resist tasting the foods. Next, different types of food that were shown in the images (including chocolate candies (M&M’s), cookies (chocolate chip Chip’s Ahoy), potato chips (Lay’s), and donuts) were made available and the participants were told that they could help themselves to the food while the investigators were in a different room. All of the provided foods were weighed before and after each free-eating session.

At the completion of each appointment participants were assessed for adverse effects of the stimulation. At the end of the second appointment participants were debriefed and they were asked to guess whether they received real or sham stimulation at each session, as well as how confident they were in their guess.

Real tDCS condition

A single 20-min tDCS session was conducted with the Phoresor-II Auto (Model PM850, Iomed, Salt Lake City Utah, USA) using 2.0 mA current. The international 10–20 EEG system was used to locate the left (F3) and right (F4) dorsolateral prefrontal cortices. The anode was placed over F4 and the cathode was placed over F3. Electrodes were standard sponge electrodes soaked in a sterile solution of .9% sodium chloride insulated by a latex casing. The current density and total charge delivered by the above parameters is consistent with those that have been used safely in previous tDCS studies (Iyer et al., 2005).

Sham tDCS procedures

For sham tDCS, the same methods were used in order to place the anode and cathode, however, the tDCS device was turned up to 2 mA for 30 s, then slowly ramped-down to 0 mA over the period of 1-min, and finally turned off for the duration of the 20-min session. This allowed the participants to sense the initial sensation associated with turning the device on (e.g., tingling and itching), but they received no active stimulation for the remainder of the 20-min session. Gandiga et al. (2006) showed this method of tDCS sham stimulation to be reliable, and it is currently the standard approach to creating a sham condition of tDCS for clinical trials.
Results

Validity of the sham tDCS treatment

At the end of the participants' second appointment, they were asked to guess which tDCS session was real and which was sham. The expected rate for correct guessing is 50% but 79% of participants guessed correctly ($\chi^2(1, N = 19) = 6.34, p = .012$), suggesting that participants were able to identify whether they were receiving real or sham tDCS at a rate better than chance. Upon follow-up, 73% of participants that guessed correctly reported that their guesses were based on a noticeable difference in cravings between the tDCS sessions and not due to differences in the experience of tDCS itself. Participants were also asked how confident they were in their guess on a scale from 0 to 10 (where 0 = “completely guessing” and 10 = “absolutely sure”). The mean of the confidence ratings was 6.45 (SD = 2.70). Because most participants correctly guessed when they received real and when they received sham tDCS, a composite index was created to control for correct-guessing in the mixed-model analysis. A new variable was created wherein the “guess-correct” value (0 = incorrect guess, 1 = correct guess) was multiplied by the guess confidence rating for each participant. Thus, those that guessed incorrectly had a guess-composite value of 0 whereas those that guessed correctly had a value equal to their guess confidence.

The relationship among cravings and tDCS condition

Bivariate correlations revealed no significant relationship between hours since last ate and tDCS effects on cravings. A 3 x 2 mixed model was run using SAS software to evaluate the interaction between stimulation timing (pre-tDCS, during tDCS, post-tDCS) and stimulation condition (real versus sham) on cravings ratings after controlling for guess-confidence. Participants’ intercepts were entered into the model as random effects at level-1 (Singer, 1998). A significant interaction between time and condition was observed on cravings ratings controlling for guess confidence ($F(5, 2717) = 9.82, p < .001$). Post hoc analyses suggest that there was a marginal difference in percent change from pre- to during-real tDCS ($M = 23.35\%$, $SD = 28.04$) compared to sham tDCS ($M = 9.00\%, SD = 39.17$; $t(18) = -1.94, p = .068$). The percent change in cravings from pre- to post-stimulation was significantly greater for real stimulation ($M = 26.81\%, SD = 26.11$) than for sham ($M = 7.98\%, SD = 41.87$; $t(18) = -2.28, p = .035$) and represented a medium-sized effect (Cohen’s $d = .55$). Figure 1 shows the percent change in cravings for real and sham tDCS.

The relationship among cravings for specific food groups and tDCS condition

Further post hoc analyses were conducted to assess whether there were differences in the change in food cravings ratings when examining individual food groups (sweets, fast-food fats, high fats, and carbohydrates) between real and sham tDCS. Results suggest that active prefrontal tDCS acutely and significantly decreased cravings ratings for sweet food and carbohydrate food images more so than sham tDCS, but no significant effects were observed for high-fat food or fast-food images. There was a significant difference in change in cravings for sweet foods between real and sham tDCS ($t(18) = -2.34, p = .031$; Real tDCS $M = 30.50\%, SD = 23.03$; Sham tDCS $M = -0.95\%, SD = 59.85$). When examining the change in cravings ratings for carbohydrate foods there was a significant difference in the change from pre- to during-stimulation between real and sham tDCS conditions ($t(18) = 2.44, p = .025$; Real tDCS $M = -24.41\%, SD = 41.67$; Sham tDCS $M = 22.10\%, SD = 79.12$). A marginal difference was observed for the change in cravings between real ($M = 25.45\%, SD = 45.60$) and sham ($M = 14.87\%, SD = 70.12$) tDCS from pre- to post-stimulation ($t(18) = -2.10, p = .032$).

The relationship among the inability to resist food and tDCS condition

A 3 x 2 mixed model was run using SAS software to evaluate the interaction between stimulation timing (pre-tDCS, during tDCS, post-tDCS) and stimulation condition (real versus sham) on ratings of inability to resist foods after controlling for guess confidence. Participants’ intercepts were entered into the model as random effects at level-1. A significant time by condition interaction effect was observed ($F(5, 2717) = 11.84, p < .001$). Post hoc analyses suggest that the inability to resist food from pre- to during-stimulation was reduced by 26.79% (SD = 33.71) in the real condition compared to 10.66% (SD = 39.57) for sham ($t(18) = -2.33, p = .031$). When examining the percent change in inability to resist food from pre- to post-stimulation there was also a greater decrease in the real tDCS condition ($M = 30.36\%, SD = 30.82$) than for sham ($M = 13.38\%, SD = 39.52$; $t(18) = -2.28, p = .035$). Figure 2 shows the percent change in inability to resist foods for real and sham tDCS conditions.

The relationship of the inability to resist specific food groups and tDCS condition

Active prefrontal tDCS acutely and significantly decreased ratings of inability to resist sweet foods more so than sham tDCS.

![Fig. 1. Mean percent change in cravings ratings in real and sham tDCS conditions.](image1)

![Fig. 2. Mean percent change in inability to resist food ratings in real and sham tDCS conditions.](image2)
findings from Fregni et al. (2008), these results suggest that active change in self-reported cravings from pre- to post-stimulation was cravings. Food cravings were reduced regardless of whether to resist foods among individuals who reported frequent food left prefrontal cortex) on self-reported food cravings and the ability to resist foods among individuals who reported frequent food cravings. Functional neuroimaging studies have shown specific brain areas, including the DLPFC, are associated with drug and alcohol cravings (Anton, 1999; Boggio et al., 2008; George et al., 2001). Similarly, previous studies have suggested that the prefrontal cortex may be involved in inhibition of food cravings in both animals and humans. Yet very few studies have attempted to directly manipulate activation of the DLPFC utilizing tDCS. Particularly, this study was one of the first to use tDCS to examine self-reported food cravings and the ability to resist food. This study also examined the effects of tDCS on cravings and the inability-to-resist across different food groups (sweets, carbohydrates, fast-food fats and high fats). The within-subjects design allowed participants to act as their own control, and therefore potential carry-over effects were minimized by randomizing real and sham tDCS sessions.

There are several limitations to the current study. The sample used for the current study was small with only 19 participants. Use of a small sample size can raise threats to external validity. However, the participants served as their own controls for subjective food cravings. Although our results indicate the percent change in self-reported cravings from pre- to post-stimulation was significantly greater for real stimulation, food cravings were reduced regardless of whether participants received real or sham tDCS. It is unknown if there was a placebo effect of the sham tDCS as effects have been shown even when participants are aware they are receiving placebo (Kaptchuk, Friedlander, Kelley, Sanchez, & Kokkotou, 2010). Regarding generalizability, the sample used in this study consisted of healthy individuals with a mean BMI of 27.25 (SD = 6.24). Although 57.9% of the participants are classified as being overweight or obese, according to their BMI, it is not known if similar effects would be observed in a sample of obese individuals, or individuals with an eating disorder. The International Affective Picture System is a reasonable and widely used system for assessing cravings in a laboratory setting, as are subjective ratings to assess food cravings and ability to resist food (CVAS). However, it is possible that the laboratory paradigm employed in this study does not elicit responses that generalize to real-world eating or craving behaviors. In fact, no significant effects were observed for tDCS on our more ecologically valid free-eating measure. A possible reason for the difference in subjective cravings not translating into the amount of food ingested between the groups is that subjective ratings of food cravings and the ability to resist food were the primary outcome variables. Therefore, the participants were selected based on self-reported cravings, determined by the FCI (White et al., 2002), rather than their food intake. The free-eating session also was a strange setting to promote eating, as it was conducted in a laboratory setting. Therefore we are not able to generalize cravings to real world eating behaviors. Future studies should include a natural observation of food consumption during a mealtime later in the day or the following day.

Results from this study suggest that tDCS may be capable of inhibiting food cravings and perceived ability to resist eating. In our study, no efforts were made to assess or manipulate mental activity during the active or sham tDCS session. This may be important as the mental activity that participants engage in during the tDCS may alter the outcomes. For example, it is not known whether having participants engage in cognitive tasks geared toward inhibiting cravings during stimulation might enhance the impact of tDCS. Additionally, real-time fMRI has shown potential to be applied as a biofeedback intervention (deCharms, 2007, 2008; Posse et al., 2003). Future studies might examine the effects of combined tDCS with cognitive interventions and real-time fMRI to alter focal brain activation and subjective food cravings. Such studies might yield data relevant to the feasibility and utility of combined neuro-stimulation and neuro-imaging interventions as stand-alone or adjunctive strategies for the prevention and management of obesity. In conclusion, active prefrontal tDCS can temporarily modify self-reported food cravings and the ability to resist foods in healthy participants during and shortly after stimulation. Additionally, active prefrontal tDCS acutely and significantly decreased food cravings for sweet foods and carbohydrates more so than did sham tDCS. These findings support those of Fregni et al. (2008), and extend them to suggest that perhaps the observed decrease in cravings elicited by prefrontal tDCS stems from enhanced activation of neuro-cognitive and behavioral inhibition networks.
associated with the observed significant effect of tDCS on participants’ subjective reported ability to resist eating.

References


