No effect of prefrontal transcranial direct current stimulation (tDCS) on food craving, food reward and subjective appetite in females displaying mild-to-moderate binge-type behaviour.

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Research report

No effect of prefrontal transcranial direct current stimulation (tDCS) on food craving, food reward and subjective appetite in females displaying mild-to-moderate binge-type behaviour

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ABSTRACT

Previous work suggests there may be an effect of transcranial direct current stimulation (tDCS) on appetite control in people at risk of overconsumption, however findings are inconsistent. This study aimed to further understand the potential eating behaviour trait-dependent effect of tDCS, specifically in those with binge-type behaviour. Seventeen females (23 ± 7 years, 25.4 ± 3.8 kg m^{-2}) with mild-to-moderate binge eating behaviour completed two sessions of double-blind, randomised and counterbalanced anodal and sham tDCS applied over the right dorsolateral prefrontal cortex at 2.0 mA for 20 min. Subjective appetite visual analogue scales (VAS), the Food Craving Questionnaire-State (FCQ-S), and Leeds Food Preference Questionnaire (LFPQ) were completed pre- and post-tDCS. Participants then consumed a fixed-energy meal, followed by the VAS, FCQ-S and LFPQ. No difference between pre- and post-tDCS scores were found across fullness ($p = 0.275$, $BF_{10} = 0.040$), prospective consumption ($p = 0.127$, $BF_{10} = 0.063$), desire to eat ($p = 0.247$, $BF_{10} = 0.054$) or FCQ-S measures ($p = 0.918$, $BF_{10} = 0.040$) when comparing active and sham protocols. Only explicit liking and wanting for high-fat sweet foods were significantly different between conditions, with increased scores following active tDCS. When controlling for baseline hunger, the significant differences were removed ($p = 0.138$ to 0.161, $BF_{10} = 0.810$ to 1.074). The present data does not support the eating behaviour trait dependency of tDCS in a specific cohort of female participants with mild-to-moderate binge eating scores, and results align with those from individuals with healthy trait scores. This suggests participants with sub-clinical binge eating behaviour do not respond to tDCS. Future work should further explore effects in clinical and sub-clinical populations displaying susceptibility to overconsumption and weight gain.

1. Introduction

The abundance of food cues in the environment and the wide availability and low cost of energy-dense, palatable foods are leading contributors to the growing levels of obesity in most societies (Berthoud, 2006; Lowe et al., 2019; Stroebe et al., 2008). These foods are associated with a pleasure response, which increases their consumption and potentiates energy dysregulation by overriding homeostatic mechanisms (Blundell, 2006; Boswell & Kober, 2016). Individuals who present with binge eating disorder (BED) and eating behaviour trait suggesting susceptibility to overconsume (e.g., emotional eating) appear to be hyper-responsive to the rewarding aspects of food (Dalton et al., 2013; Davis, 2009, 2013). Accompanied by a sense of lack of control, BED is characterised by recurrent episodes of excessive consumption (American Psychiatric Association, 2013). This disorder is estimated to affect 0.7–3.0% of the general population, and is commonly comorbid with overweight and obesity (Kessler et al., 2013). Recurrent, mild-to-moderate binge eating episodes are estimated to occur in 10–20% of individuals who are healthy weight, overweight and obese, and constitutes a trait that can be assessed psychometrically and applied

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to a non-clinical population. The control of hedonic-driven appetite poses an important step in the treatment of obesity and disordered eating.

One route to controlling hedonic appetite involves executive functioning, associated with activity within the prefrontal cortex (PFC). Through these functions, impulsive actions may be inhibited in favour of goal-directed behaviours (Joseph et al., 2011). It has been proposed that poor appetite control is the result of reduced activity specifically within the dorsolateral PFC (DLPFC) (Alonso-Alonso & Pascual-Leone, 2007; Gluck et al., 2017). Indeed, those with obesity and/or BED appear to have hypo-activation of the PFC and display impairments in executive functioning (Blume et al., 2019; Boeka & Lokken, 2011; Cserjési et al., 2009; Karhunen et al., 2000; Michaud et al., 2017). Therefore, increasing activity within the DLPFC may improve the ability to control appetite, potentially providing a novel treatment option for obesity (Alonso-Alonso, 2013).

It is possible to alter cortical activity through non-invasive brain stimulation (NIBS) techniques (Jamil & Nitsche, 2017; Yavari et al., 2017). Transcranial direct current stimulation (tDCS) is a form of NIBS that involves the application of a weak electrical current to a specific region of the brain via two electrodes that are placed over the scalp (Nitsche & Paulus, 2000; Priori et al., 1998). The current, typically applied offline (i.e., while the participant is at rest and not completing other tasks), is emitted from a 9V battery-powered device and travels from an anode electrode through the brain and returns to the device via a cathode electrode. The current strength is relatively low, typically only up to 2.0 milliampere (mA), which is not sufficient to cause neuronal firing (Filmer et al., 2014; Jamil & Nitsche, 2017). Instead, tDCS appears able to modulate subthreshold resting membrane potentials in a polarity-dependent manner through the inhibition of neurotransmitters at the synapse (Filmer et al., 2014; Jamil & Nitsche, 2017). For example, resting membrane potentials can be depolarised under the anode through the inhibition of gamma-aminobutyric acid (GABA). In comparison, the inhibition of glutamate under the cathode results in the hyperpolarisation of resting membrane potentials (Filmer et al., 2014). The inhibition of these neurotransmitters results in the increased (anodal "excitatory" tDCS) or decreased (cathodal "inhibitory" tDCS) likelihood of spontaneous neuronal firing, respectively.

This technique is a popular method for modulating cortical activity due to its simplicity, scalability and low cost (Thair et al., 2017), and is considered safe for many populations, including healthy individuals and patient groups (Matsumoto & Ugawa, 2017). The popularity of tDCS has seen a proliferation of publications examining the effects of this technique in altering eating behaviour. The first of these studies found significantly reduced cravings following 20 min of tDCS in a population displaying frequent food cravings (i.e., experiencing 3 or more strong urges to consume high-calorie foods per day) (Fregni et al., 2008). Despite these promising results, further research has shown an inconsistent effect of tDCS across measures of food craving and consumption (Georgii et al., 2017; Gluck et al., 2015; Goldman et al., 2011; Sedgmond et al., 2019). One possible explanation for the discrepancy in results are the behaviour traits of participants recruited to each study (Beaumont et al., 2022b). One example is the significant reduction in measures of food craving and consumption shown in participants displaying binge eating behaviour, but not in a population with frank obesity (i.e., non-binge eating) (Burgess et al., 2016; Ray et al., 2017). In addition, data from our own group did not find a significant effect of tDCS across measures of food craving, food reward and subjective appetite in a healthy-weight population who do not show susceptibility to overconsumption or weight gain (Beaumont et al., 2021). As such, only individuals who present with sub-clinical or clinical eating behaviour traits suggesting susceptibility to overconsumption and weight gain – i.e., those with heightened responsiveness to the rewarding aspects of food and/or showing diminished executive functioning (e.g., those experiencing frequent food cravings, those with binge-type behaviour) – appear responsive to the effects of tDCS (Beaumont et al., 2022b).

To extend the findings of the above work, the present study looked to evaluate the effects of offline tDCS on food craving, food reward and subjective appetite in a cohort displaying mild-to-moderate binge eating behaviour. This work is also the first to explore the effects of tDCS in the fasted and fed states. Our prior study showed good reliability of food reward measures, and here we extend these to examine the effects in those susceptible to hedonic-driven consumption. We hypothesised that: (i) active tDCS would reduce participants' subjective appetite, and the craving and preference for foods, and; (ii) food craving and reward will be reduced following the consumption of a standardised meal under both active and sham conditions, with greater reduction seen following active tDCS.

2. Methods

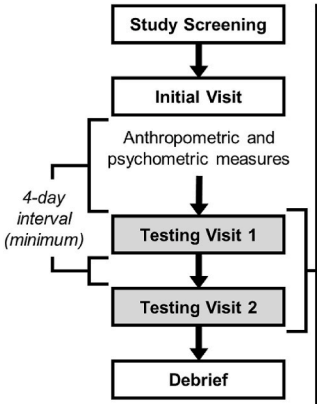
2.1. Participants

The study was conducted across two institutions (Leeds Trinity University and University of Leeds, UK) and approved at both by the relevant ethics committees (LTU: SSHS-2019-023/UoL: PSC-880). All participants provided their written informed consent. Sample size was calculated using G*Power 3.0.10 (Faul et al., 2007) using mean percentage difference from baseline in food craving scores following tDCS (Fregni et al., 2008; Goldman et al., 2011; Kekic et al., 2014; Ljubisavljevic et al., 2016). A minimum sample size of 17 was determined using effect size f of 0.33, α error probability of 0.05, 1 group with 3 measurements, a correlation among repeated measures equal to 0.5, and non-sphericity correlation Є of 1. This provided actual power of 0.82. A total of 24 participants were recruited via email, poster and participant database advertisements. As a consequence of the COVID-19 pandemic, attrition of seven participants occurred due to relocating to another part of country, returning to their home country, or feeling uncomfortable attending visits.

Interested individuals were initially screened with an online questionnaire. Eligible participants were between 18 and 60 years of age. Due to apparent differences in eating behaviour between males and females (Rolls et al., 1991), the present study recruited only female participants in line with prior research (Chen et al., 2019; Kekic et al., 2014; Mattavelli et al., 2019; To et al., 2018). Based on pre-screening questionnaire responses, all participants self-reported that they were free of neurological, cardiovascular, metabolic, and joint disease and were not pregnant or wishing to conceive. Due to the link between depression and altered prefrontal cortex activity (Nitsche et al., 2009), potential participants were excluded if they presented with low mood or symptoms of depression, as indicated by the Centre for Epidemiologic Studies Short Depression Scale (CESD-10) (Andresen et al., 1994). In addition, participants were naïve to tDCS protocols, were non-smokers and did not use recreational drugs or medications at the time of data collection. Only participants who presented with mild-to-moderate binge eating behaviour were included in the study, as indicated using the Binge Eating Scale (BES) (see section 2.5.1). Finally, participants were required to like the fixed-energy test meal, with a score of four or greater for liking of the test meal on a seven-point scale (see section 2.6).

2.2. Experimental design

The present study adhered to a double-blind, within-participant, repeated-measures design. Participants attended the laboratory on three separate occasions (Fig. 1). The first visit involved the completion of psychometric and anthropometric measures. The second and third visit were experimental trials where participants received either active or sham tDCS in a randomised and counterbalanced order. Randomisation was determined using a permuted block paradigm and completed by an independent researcher. This independent researcher pre-set the tDCS parameters via a pin-protected programme device; the researcher conducting tDCS was provided with a separate stimulation device and could



Time (min)	Task
0	Baseline Questionnaire (adherence to fasting criteria)
2	Questionnaires (pre-tDCS): Appetite VAS → FCQ-S → LFPQ
17	tDCS preparatory procedures
22	Active or Sham tDCS (randomised and counterbalanced)
42	Adverse Events Questionnaire
45	Questionnaires (post-tDCS): Appetite VAS → FCQ-S → LFPQ
60	Adverse Events Questionnaire
63	Standardised meal (cheese sandwich)
73	Appetite VAS (with additional question)
75	10-minute interval
85	Adverse Events Questionnaire
88	Questionnaires (post-meal): Appetite VAS → FCQ-S → LFPQ
103	Adverse Events Questionnaire
At end of day: Control of Eating Questionnaire, 24-hour version	

Fig. 1. Study Procedure
FCQ-S, Food Craving Questionnaire-State; LFPQ, Leeds Food Preference Questionnaire; tDCS, transcranial direct current stimulation; VAS, visual analogue scales.

not access the parameter details. Participants and the researcher completing stimulation procedures were blind to the administration of tDCS condition.

2.3. Procedure

All sessions were scheduled at the same time of day within-participant, occurring between 11:30 and 14:00 to capture a typical lunch period, with a minimum interval of 4 days between sessions. Prior to each session, participants were required to fast for a minimum of 4 h where they were asked to refrain from consuming any food or drink other than water; fasting adherence was self-reported at the start of each session (Gibbons et al., 2014; Meule, 2018b). Participants were asked to consume their normal breakfast just before this fasting period, and to consume the same breakfast meal across testing days. To minimise confounding effects, participants were asked to refrain from consuming products containing caffeine and alcohol in the 12 and 24 h prior to each visit, respectively (Caton et al., 2004; Harpaz et al., 2017; Schubert et al., 2017; Yeomans et al., 2003), and to avoid moderate to vigorous physical activity in the 12 h prior to attending visits (Beaulieu et al., 2017, 2018).

In the initial visit, participants completed the Three Factor Eating Questionnaire (TFEQ), a 7-day version of the Control of Eating Questionnaire (CoEQ) and Food Craving Questionnaire-Trait-reduced (FCQ-T-r) (see 2.5.1). Height was measured to the nearest mm using a portable stadiometer (SECA Limited, Birmingham, UK). Each measurement was taken following inhalation, with the participant standing straight and their head aligned according to the Frankfurt plane. Body composition was assessed using a Tanita BC-418MA analyser (Tanita Europe B.V., Amsterdam), which included both weight and body fat percentage, measured to the nearest 0.1 kg and 0.1%, respectively. Waist and hip circumference were measured in accordance with the standardised procedure by the World Health Organisation (2008). Waist circumference was determined by identifying the midpoint between the lower margin of the last palpable rib and the top of the iliac crest. Hip circumference was measured as the widest portion of the gluteus muscle. All measurements were taken following expiration to the nearest 0.1 cm and repeated twice. If measurements varied by 2.0 cm or more, they were repeated a third time with the arithmetic mean taken thereafter. Finally, participants were shown the images used in the Leeds Food Preference Questionnaire (LFPQ) (Table 1) to assess their familiarity and acceptance of each food item. If any items were unfamiliar, disliked or not consumed as part of the normal diet they were substituted with an alternative food image from a database of additional items with similar nutritional and sensory properties (Oustric et al., 2020).

Visits 2 and 3 were identical, apart from the stimulation condition. In these sessions, participants were required to complete a series of questionnaires which included appetite visual analogue scales (VAS), the LFPQ and Food Craving Questionnaire-State (FCQ-S) (see section 2.5). These questionnaires were completed pre- and post-tDCS and repeated shortly after a standardised fixed-energy meal (see section 2.6). At the end of the day following both visit 2 and 3, participants were asked to complete a 24-h version of the CoEQ. At the end of the final visit, participants were informed of the sham stimulation condition and both participant and experimenter blinding were verified (see 2.4).

2.4. Stimulation protocol

Anodal tDCS was delivered by a trained researcher using the HDCstim device (Newronika s.r.l., Milan, Italy). Electrodes were placed in accordance with the International Standards for Electroencephalography 10–20 system (Klem et al., 1999). A 25 cm^2 anode electrode was placed over the frontal area 4 (F4) to target the right DLPFC, and a 51 cm^2 cathode was placed over the occipital zero point (Oz). The rubber electrode plates were placed in sponge pads, pre-soaked in 0.9% sodium chloride. A constant current of 2 mA was delivered, culminating in a current density of 0.08 mA cm^{-2}. The current was ramped up over a 30-s period and was then delivered for 20 min in the active condition and 36 s

Table 1
Standardised food images used in the LFPQ.

HFSA	HFSW	LFSA	LFSW
Garlic bread	Chocolate biscuits	Green salad	Mixed berry salad
Fries	Glazed doughnut	Broccoli	Skittles
Crisps	Blueberry muffin	Vegetable rice	Haribo
Sausage roll	Milk chocolate	Bread roll	Banana

HFSA, high-fat savoury; HFSW, high-fat sweet; LFSA, low-fat savoury; LFSW, low-fat sweet.

in the sham condition (3% active tDCS duration). The current was then ramped down over a 30-s period. In the sham session, participants remained seated for 20 min to mimic the protocol and match the duration of active tDCS. The shortened sham duration is associated with similar cutaneous sensations but has a limited neuromodulatory effect (Brunoni et al., 2011; Gandiga et al., 2006). Stimulation was delivered offline (i.e., no tasks were performed during tDCS), with participants asked to remain seated, relaxed, and awake.

Impedance was measured at the start of stimulation, and periodically thereafter. The occurrence of sensations and adverse events were measured immediately following tDCS using the Adverse Events Questionnaire (AEQ) (Brunoni et al., 2011). This questionnaire was repeated at regular intervals for up to 70 min post-stimulation. The use of sham tDCS as a blinding technique was assessed during debrief. The participant was asked if they were able to differentiate between the stimulation conditions, and which visit they believed active tDCS was delivered. Their confidence in this choice was assessed on a 10-point Likert scale ranging from *"Not at all confident"* to *"Very confident"*. In addition, experimenter blinding was measured through belief of stimulation condition order.

2.5. Measurements

2.5.1. Psychometric questionnaires

The BES (Gormally et al., 1982) was completed during screening; participants were presented with 16 sets of statements and required to select one statement from each set that best represents their eating behaviour. Statements were scored 0 to 2 (for sets of 3 statements) or 0 to 3 (for sets of 4 statements), with a total score ranging from 0 to 46. The BES has good internal validity (Cronbach's alpha [α] = 0.87) (Grupski et al., 2013), with a clinically relevant cut-off score of 27 (Gormally et al., 1982). Individuals were eligible to participate in the present study if they scored between 15 and 26, which highlights mild-to-moderate binge-type behaviour and a susceptibility to overconsume and gain weight, but does not indicate a clinical disorder (Dalton & Finlayson, 2014; Marcus et al., 1988).

During the initial visit, participants were asked to complete a series of questionnaires that further assessed their eating behaviour traits. The TFEQ (Stunkard & Messick, 1985) is a 51-item questionnaire measuring cognitive restraint, disinhibition and susceptibility to hunger as factors of eating behaviour. Cognitive restraint refers to the control of food consumption with the aim of controlling body weight, disinhibition is the loss of control over eating and hunger refers to the subjective feeling of hunger and food craving. These factors are measured across two parts, where participants answer true or false to a set of 36 statements (e.g., *"I often feel so hungry I just have to eat something"*) and then rate 15 items over a 4-point scale. Responses are scores 0 or 1, with total scores ranging from 0 to 21 for cognitive restraint, 0 to 16 for disinhibition, and 0 to 14 for hunger. Higher scores indicate greater prevalence of the factor. A 7-day version of the CoEQ (Dalton et al., 2015) was used to measure the frequency, intensity and severity of food cravings that participants experienced over the prior 7 days. Items are scored using 100 mm VAS, with an average score across items providing an individual score for craving control, craving for sweet foods, craving for savoury foods and positive mood. The final of these questionnaires is the FCQ-T-r (Meule et al., 2014), which assesses lack of control over eating, emotions experienced before or during food craving and consumption, and guilt from cravings and/or giving in to cravings. Participants respond to 15 items on a 6-point scale, with total scores ranging from 15 to 90. A higher score suggests more frequent habitual cravings, with a total score greater than 50 highlighting clinically relevant trait cravings (Meule, 2018a).

2.5.2. Appetite visual analogue scales

To measure subjective ratings of appetite, 100 mm VAS were used to determine hunger ("*How hungry do you feel right now?*"), fullness ("*How full do you feel right now?*"), prospective consumption ("*How much food could you eat right now?*"), and the desire to eat ("*How strong is your desire to eat right now?*") (Blundell et al., 2010). Scores range from 0 to 100, with higher scores indicating greater prevalence of the appetite measure. These VAS are sensitive to experimental manipulation and considered reliable and valid measure of subjective appetite (Beechy et al., 2012).

2.5.3. Leeds Food Preference Questionnaire

The LFPQ (Dalton & Finlayson, 2014; Finlayson et al., 2007) is a validated computer-based assessment of the hedonic preference for food, and measures liking and wanting as components of reward. "Liking" is defined as the subjective pleasure elicited by food or related cues, where as "wanting" is the motivational component of reward that refers to the subjective desire or craving for foods (Finlayson & Dalton, 2012b). Liking operates at an explicit level (i.e., conscious, introspective), and wanting at both explicit and implicit (i.e., subconscious, automatic) levels. The task uses a standardised set of 16 images depicting ready-to-eat foods that are common in the diet (Table 1). These images illustrate items that are either high (>40% energy) or low (<20% energy) in fat and either sweet or savoury, and can be split into four categories; high-fat savoury (HFSA), high-fat sweet (HFSW), low-fat savoury (LFSA), and low-fat sweet (LFSW). Food reward is assessed according to the fat content and taste of these foods, which are comparable in protein content, palatability and familiarity (Oustric et al., 2020).

The LFPQ incorporates two tasks where food items are either displayed in pairs (forced-choice task) or individually (single-food task). The forced-choice task measures the implicit wanting for foods and involves participants choosing the food they most want to consume "right now" from two items presented on the computer screen. A frequency-weighted algorithm is used to provide a score for implicit wanting, which combines reaction times with the frequency of choosing or avoiding a food (Dalton & Finlayson, 2014). In the single-food task, participants are presented with each of the 16 food items individuals and asked to rate *"How much do you want some of this food right now?"* and *"How pleasant would it be to taste some of this food right now?"*. Participants respond to each question on a 100-unit VAS that measure explicit wanting and liking, respectively. Fat appeal bias (FAB) and taste appeal bias (TAB) scores are additionally calculated for explicit liking, explicit wanting and implicit wanting. Bias scores are calculated by subtracting mean scores across food groups (e.g., mean low-fat scores are subtracted from mean high-fat scores).

2.5.4. Food craving questionnaire-state

In-the-moment food cravings were measured using the FCQ-S (Cepeda-Benito et al., 2000). Across 15 items, participants' desire to eat, craving for food and emotional responses to food and consumption are measured. Participants respond to each item on a 5-point scale, where 1 corresponds with *"Strongly disagree"* and 5 corresponds with *"Strongly agree"*. These corresponding numbers are totalled to provide a score between 15 and 75, with a higher score indicating greater momentary craving.

2.5.5. Control of Eating Questionnaire, 24-h version

In addition to the FCQ-S, a 24-h version of the CoEQ was implemented to assess for changes in craving across the entire study day. This questionnaire was completed by the participant at the end of the day following each experimental visit. The items and scoring of the questionnaire are identical to the 7-day CoEQ, but the words *"last 7 days"* were substituted for the word *"today"*.

2.6. Fixed-energy meal

To shift participants from a fasted to fed state, they were presented with a fixed-energy meal. This meal was a cheese sandwich comprising

of white bread, medium grated cheddar cheese, and sunflower spread (ASDA, UK). This test meal was chosen as it is an appropriate meal for the time of day tested (i.e., lunch), and easily allowed manipulation of calorie content to meet individual requirements (see below). These values were calculated based on the data provided by the manufacturer. Participants' liking for the meal was assessed during study screening using a seven-point Likert scale, ranging from "*Dislike extremely*" to "*Like extremely*". A score of 4 or more, indicating a liking for the meal, was required for participants to be eligible for participation (Buckland & Dalton, 2018). Food allergies and intolerances were also measured during screening; due to the potential for contamination with allergens, an individual who reported allergy to any food was excluded. Those who reported intolerance to the ingredients used (e.g., gluten and lactose intolerance) were excluded.

Test meals were presented in the same manner within-participant, i.e., environment and utensils were identical across sessions, but different laboratory spaces were used between-participants to accommodate multi-site data collection. The sandwich was presented on a plain white plate. The nutritional composition of each component is displayed in the supporting material (Table S1); each component of the sandwich were measured to the nearest 0.1g, with weight of the cheese and sunflower spread adjusted so the sandwich would provide sufficient energy to meet 30% resting metabolic rate (RMR) for each participant (Buckland & Dalton, 2018). The RMR was estimated using the Mifflin-St Joer equation (Mifflin et al., 1990). This equation is suitable for individuals with healthy weight or obesity due to a high accuracy and small error ranges in both populations (Frankenfield et al., 2005). The composition, energy content and nutritional content of the cheese sandwich are displayed in the supporting material (Tables S2 and S3). One litre of water was provided for the participant to consume as desired, presented in a clear glassware, and was measured following consumption.

The use of laboratory-based measures of food intake allow for control of the environment in which a participant consumes food, isolating the participant from confounding factors (Best et al., 2018). However, the presence of others and of distractions such as mobile phones can influence the consumptive behaviour of an individual (Buckland & Dalton, 2018; Herman et al., 2003). Participants were required to turn off their mobile phone and place this with their belongings away from the testing area at the beginning of each visit. Participants were instructed to consume the entire sandwich and were left to consume alone for 10 min in a quiet environment. Immediately following the test meal, participants were given a copy of the appetite VAS, with an additional question to assess participants' liking of the cheese sandwich ("*How pleasant did you find the meal?*").

2.7. Data analysis

Mean and standard deviations (SD) were calculated for each time point (pre-tDCS, post-tDCS, post-meal) under active and sham conditions. Normality of data were assessed using Shapiro-Wilks test. To allow comparison with data from our prior work (Beaumont et al., 2021), the effects of tDCS on appetite VAS, LFPQ and FCQ-S scores were initially evaluated using a 2 (condition; active or sham) by 2 (time point; pre-tDCS, post-tDCS) repeated measures analysis of variance (ANOVA). To determine the effects of the standardised meal, additional 2 (condition; active or sham) by 3 (time point; pre-tDCS, post-tDCS, post-meal) repeated-measured ANOVA were conducted. Partial eta squared (η_p^2) were used to indicate ANOVA effect size. Pair-wise comparisons with Bonferroni corrections were used to determine post-hoc significant effects.

To control for the observed difference in hunger scores at baseline, analysis of covariance (ANCOVA) were performed to determine whether significant changes in measures were driven by baseline hunger. Paired-samples t-tests were used to compare differences in adverse events. Non-parametric pair-wise comparisons were analysed using Wilcoxon signed-rank test. To interpret the findings and assess the strength of evidence, Bayesian statistics were computed. Bayes factors (BF_{10}) were interpreted using the classification scheme by Lee and Wagenmakers (2013). Briefly, a factor below 1 provides evidence in favour of the null hypothesis, and a factor greater than 1 provides evidence in favour of the experimental hypothesis. Scores are classed as anecdotal (BF_{10} between 0.33 and 3), moderate (BF_{10} between 0.10 and 0.33, or 3 and 10), strong (BF_{10} between 0.03 and 0.10, or 10 and 30), very strong (BF_{10} between 0.01 and 0.03, or 30 and 100), or extreme (BF_{10} lesser than 0.01, or greater than 100). All statistical analyses were performed using JASP version 0.16.2.0 (University of Amsterdam, Amsterdam, The Netherlands).

Data for the 24-h CoEQ were missing for three participants due to the participants losing the questionnaire (n = 1 participant, 1 questionnaire), or loss of contact during the COVID-19 pandemic (n = 2 participants, 3 questionnaires). Due to technical issues, data for the LFPQ were missing for the post-tDCS time point in the active session for one participant.

3. Results

Demographic, anthropometric and eating behaviour trait characteristics are displayed in Table 2. Participants were weight stable (±5%) for 3 months prior to the study and were mainly healthy weight (n = 9), with six participants classified as overweight, and two as obese. All participants had a waist-to-hip ratio above the recommended levels (range: 1.1 to 1.4 AU) (World Health Organisation, 2008). Most participants (n = 12) had FCQ-T-r scores above the cut-off for clinically relevant trait cravings (range: 44 to 82 AU), with BES scores suggesting mild (n = 2; range: 15 to 17 AU) and moderate (n = 15; range: 18 to 26) binge eating behaviour. Across the 7-day CoEQ, participants presented with lower craving control scores, and higher craving for sweet foods when compared to "healthy" counterparts (Beaumont et al., 2021).

Table 2
Summary of participant demographic, anthropometric and psychometric characteristics.

		n (%)
Ethnicity	White	12 (70.6)
	Asian or Asian British	3 (17.6)
	Mixed or multiple ethnicity	2 (11.8)
Education	Attained university degree	8 (47.1)
	Not attained university degree	9 (52.9)
		mean ± SD
Age (years)		23 ± 7
Height (cm)		164.8 ± 9.0
Weight (kg)		69.1 ± 12.0
BMI ($kg{\cdot}m^{-2}$)		25.4 ± 3.8
Body fat (kg)		45.3 ± 4.7
Body fat (%)		33.4 ± 5.9
Waist circumference (cm)		82.2 ± 9.5
Hip circumference (cm)		102.8 ± 8.4
Waist-to-Hip Ratio (AU)		1.3 ± 0.1
CESD-10 (AU)		9 ± 5
BES score (AU)		21 ± 4
FCQ-T-r (AU)		57 ± 10
TFEQ Cognitive Restraint (AU)		10 ± 4
TFEQ Disinhibition (AU)		11 ± 3
TFEQ Hunger (AU)		8 ± 3
CoEQ (7-day) Craving Control (mm)		48 ± 20
CoEQ (7-day) Craving for Sweet Foods (mm)		49 ± 25
CoEQ (7-day) Craving for Savoury Foods (mm)		58 ± 21
CoEQ (7-day) Positive Mood (mm)		45 ± 10

AU, arbitrary unit; BES, Binge Eating Scale BMI, Body Mass Index; CESD-10, Centre for Epidemiologic Studies Short Depression Scale; CoEQ, Control of Eating Questionnaire; FCQ-T-r, Food Craving Questionnaire-Trait reduced form; TFEQ, Three Factor Eating Questionnaire.

3.1. Standardised meal

Overall, participants rated the meal as moderately pleasant (active session 62.3 ± 19.7 mm, sham session 64.4 ± 20.7 mm), with no difference in score between active and sham conditions ($t_{(16)} = 0.874$, $p = 0.395$, $BF_{10} = 0.348$). There was no difference in consumption of water during both active (346 ± 273 ml) and sham sessions (378 ± 327 ml) ($z = 0.052$, $p = 0.979$). Consumption of the test meal had the expected effects on study measures; hunger, prospective consumption, desire to eat and FCQ-S scores were all reduced following consumption, with fullness VAS scores increasing after consumption (see the following sections).

3.2. Appetite visual analogue scales

Despite no difference in fasting duration when comparing active (5.39 ± 2.87 h) and sham conditions (5.08 ± 2.58 h) ($t_{(16)} = 0.888$, $p = 0.215$, $BF_{10} = 0.351$), hunger scores were significantly higher at baseline in the sham tDCS session ($z = -2.130$, $p = 0.035$, $BF_{10} = 2.806$) (Table 3). There were no differences when comparing active and sham protocols for hunger ($F_{(1.953,\ 29.301)} = 2.926$, $p = 0.071$, $\eta_p^2 = 0.163$), fullness ($F_{(3,\ 45)} = 0.502$, $p = 0.683$, $\eta_p^2 = 0.045$), prospective consumption ($F_{(3,\ 45)} = 0.704$, $p = 0.554$, $\eta_p^2 = 0.032$), or desire to eat scores ($F_{(3,\ 45)} = 0.777$, $p = 0.513$, $\eta_p^2 = 0.049$) (Table 3). However, each of these comparisons is supported by extreme evidence for the alternative hypothesis (hunger $BF_{10} = 2.009e + 12$, fullness $BF_{10} = 9.363e + 12$, prospective consumption $BF_{10} = 5.815e + 9$, and desire to eat $BF_{10} = 105{,}758.472$), supporting an experimental effect in the active tDCS condition.

Of interest, while hunger levels were higher at the start of the sham session, there was a significant change pre-to post-tDCS where hunger levels following active tDCS increased to match those of post-sham stimulation ($F_{(1,\ 15)} = 6.796$, $p = 0.020$, $\eta_p^2 = 0.312$, $BF_{10} = 0.188$). When controlling for baseline hunger, this effect was no longer significant ($F_{(1,\ 30)} = 0.610$, $p = 0.441$, $\eta_p^2 = 0.020$, $BF_{10} = 0.680$). No significant differences were seen when comparing active and sham tDCS for measures of fullness ($F_{(1,\ 15)} = 1.282$, $p = 0.275$, $\eta_p^2 = 0.079$, $BF_{10} = 0.040$), prospective consumption ($F_{(1,\ 15)} = 2.606$, $p = 0.127$, $\eta_p^2 = 0.148$, $BF_{10} = 0.063$) and desire to eat ($F_{(1,\ 15)} = 1.452$, $p = 0.247$, $\eta_p^2 = 0.088$, $BF_{10} = 0.054$), with Bayes factors suggesting moderate-to-strong evidence in favour of the null hypothesis.

3.3. Leeds Food Preference Questionnaire

Only explicit liking for HFSW was significantly different between conditions, with scores increasing following active versus sham tDCS ($F_{(2,\ 30)} = 6.814$, $p = 0.008$, $\eta_p^2 = 0.312$, $BF_{10} = 356.532$) (Table 4; Table S4) in the opposite direction than originally hypothesised. Explicit wanting for HFSW foods followed a similar pattern as explicit liking scores, but this only neared significance ($F_{(1.460,\ 21.897)} = 3.715$, $p = 0.053$, $\eta_p^2 = 0.199$, $BF_{10} = 6.273$) (Table 4; Table S5). Implicit wanting for this food category did not differ between active and sham conditions ($F_{(1.339,\ 20.083)} = 0.598$, $p = 0.495$, $\eta_p^2 = 0.038$, $BF_{10} = 0.020$) (Table 4; Table S6).

When considering explicit liking for the other food categories, there were no differences observed for HFSA ($F_{(2,\ 30)} = 1.113$, $p = 0.342$, $\eta_p^2 = 0.069$, $BF_{10} = 880.990$), LFSA ($F_{(2,\ 30)} = 0.756$, $p = 0.478$, $\eta_p^2 = 0.048$, $BF_{10} = 10{,}368.165$), or LFSW foods ($F_{(2,\ 30)} = 2.685$, $p = 0.085$, $\eta_p^2 = 0.152$, $BF_{10} = 0.162$). Similarly, there were no significant differences observed for the explicit wanting of HFSA ($F_{(2,\ 30)} = 0.967$, $p = 0.392$, $\eta_p^2 = 0.061$, $BF_{10} = 31{,}477.412$), LFSA ($F_{(2,\ 30)} = 0.254$, $p = 0.778$, $\eta_p^2 = 0.017$, $BF_{10} = 1266.114$), or LFSW foods ($F_{(2,\ 30)} = 1.969$, $p = 0.157$, $\eta_p^2 = 0.116$, $BF_{10} = 8.553$). Implicit wanting scores for HFSA ($F_{(2,\ 30)} = 0.016$, $p = 0.984$, $\eta_p^2 = 0.001$, $BF_{10} = 0.989$), LFSA ($F_{(2,\ 30)} = 1.483$, $p = 0.243$, $\eta_p^2 = 0.090$, $BF_{10} = 0.261$), and LFSW foods ($F_{(1.477,\ 22.148)} = 1.586$, $p = 0.227$, $\eta_p^2 = 0.096$, $BF_{10} = 0.370$) were not significantly different between conditions, and these effects were supported by anecdotal-to-moderate evidence in favour of the null hypothesis. When considering FAB scores, there were no differences when comparing active and sham tDCS across measures of explicit liking ($F_{(2,\ 30)} = 0.775$, $p = 0.470$, $\eta_p^2 = 0.049$, $BF_{10} = 0.033$), explicit wanting ($F_{(2,\ 30)} = 0.663$, $p = 0.523$, $\eta_p^2 = 0.042$, $BF_{10} = 0.008$), or implicit wanting ($F_{(2,\ 30)} = 0.460$, $p = 0.636$, $\eta_p^2 = 0.030$, $BF_{10} = 0.027$). There were no significant effects observed for TAB scores across explicit liking ($F_{(2,\ 30)} = 2.341$, $p = 0.114$, $\eta_p^2 = 0.135$, $BF_{10} = 2.053$), explicit wanting ($F_{(2,\ 30)} = 2.663$, $p = 0.086$, $\eta_p^2 = 0.151$, $BF_{10} = 0.644$), and implicit wanting measures ($F_{(1.338,\ 20.007)} = 0.807$, $p = 0.414$, $\eta_p^2 = 0.051$, $BF_{10} = 2.808$).

A similar pattern of effects was observed when comparing only pre- and post-tDCS scores across all measures (Table S7). No significant effects were observed across measures, except for explicit liking and wanting for HFSW foods. For both explicit liking and wanting, the preference for HFSW foods increased following active tDCS and decreased following sham tDCS. To determine whether these significant

Table 3
Mean ± SD appetite visual analogue scale (VAS) scores prior to and following tDCS intervention (n = 17).

		Hunger (mm)	Fullness (mm)	Prospective Consumption (mm)	Desire to Eat (mm)
Baseline (pre-tDCS)	Active tDCS	49.1 ± 25.9 *	32.1 ± 18.0	52.9 ± 21.2	50.6 ± 27.8
	Sham tDCS	62.1 ± 18.0 *	25.0 ± 18.7	57.8 ± 17.2	56.5 ± 28.0
Post-tDCS	Active tDCS	56.3 ± 23.8	28.3 ± 18.2	59.1 ± 17.4	60.4 ± 20.7
	Sham tDCS	56.5 ± 25.9	28.6 ± 20.9	58.8 ± 23.2	56.7 ± 25.9
0 min post-meal	Active tDCS	27.9 ± 21.1	61.9 ± 21.7	33.5 ± 18.8	32.6 ± 24.6
	Sham tDCS	30.8 ± 23.1	60.9 ± 20.8	36.0 ± 20.1	34.5 ± 25.7
10 min post-meal	Active tDCS	27.0 ± 19.2	64.3 ± 17.5	33.1 ± 18.9	34.8 ± 21.1
	Sham tDCS	29.9 ± 21.2	59.7 ± 18.5	37.0 ± 22.8	31.2 ± 24.4

*$p < 0.05$ for comparison between active and sham protocols.

Table 4
Mean ± SD data for appeal bias scores (n = 17).

	Condition	Timepoint	FAB (mm)	TAB (mm)
Explicit liking	Active	Pre-tDCS	3.3 ± 17.7	1.5 ± 10.2
		Post-tDCS	7.7 ± 11.8	6.9 ± 16.6
		Post-meal	3.1 ± 11.7	13.8 ± 19.6
	Sham	Pre-tDCS	6.1 ± 12.8	5.6 ± 13.4
		Post-tDCS	7.2 ± 15.5	3.0 ± 8.1
		Post-meal	1.4 ± 14.7	9.7 ± 16.4
Explicit wanting	Active	Pre-tDCS	2.6 ± 15.2	0.9 ± 12.6
		Post-tDCS	4.4 ± 13.2	5.8 ± 17.2
		Post-meal	1.9 ± 14.9	11.1 ± 17.4
	Sham	Pre-tDCS	5.8 ± 16.4	3.2 ± 11.8
		Post-tDCS	4.6 ± 15.8	−1.8 ± 10.8
		Post-meal	1.5 ± 15.2	7.1 ± 13.2
Implicit wanting	Active	Pre-tDCS	9.9 ± 22.8	1.9 ± 28.3
		Post-tDCS	11.1 ± 24.2	−6.9 ± 31.5
		Post-meal	2.3 ± 26.3	8.9 ± 32.9
	Sham	Pre-tDCS	12.7 ± 28.3	−6.0 ± 35.9
		Post-tDCS	8.5 ± 25.0	−15.2 ± 24.1
		Post-meal	2.5 ± 16.8	10.7 ± 37.4

FAB, fat appeal bias; TAB, taste appeal bias.

effects were driven by the difference in baseline hunger, ANCOVA were performed; the difference between pre- and post-tDCS was no longer significant when controlling for hunger (explicit liking $F_{(1, 30)} = 2.061$, $p = 0.161$, $\eta_p^2 = 0.064$, $BF_{10} = 1.074$; explicit wanting $F_{(1, 30)} = 2.319$, $p = 0.138$, $\eta_p^2 = 0.072$, $BF_{10} = 0.810$). Across most measures, Bayes factors suggest anecdotal-to-strong evidence in favour of the null hypothesis. Only explicit liking for LFSA and HFSW foods and the implicit wanting for LFSA were supported by evidence in favour of the alternative hypothesis, but the strength of evidence was only anecdotal.

3.4. Food craving questionnaire-state

When comparing data across all three time points, there was no difference in food craving scores following active (baseline 44.2 ± 10.1 AU, post-tDCS 43.5 ± 14.5 AU, post-meal 36.4 ± 10.7 AU) versus sham protocols (baseline 46.5 ± 7.4 AU, post-tDCS 45.4 ± 10.7 AU, post-meal 34.9 ± 8.9 AU) ($F_{(2, 32)} = 0.852$, $p = 0.436$, $\eta_p^2 = 0.051$) (Fig. 2). However, Bayes factor analysis revealed extreme evidence in favour of the alternative hypothesis ($BF_{10} = 985.182$). When post-meal data were removed from analyses, the effect remained non-significant ($F_{(1, 16)} = 0.011$, $p = 0.918$, $\eta_p^2 < 0.001$) but Bayes factors suggest strong evidence in favour of the null hypothesis ($BF_{10} = 0.040$).

3.5. Control of Eating Questionnaire, 24-h version

Scores for craving control (active 59.1 ± 18.4 mm, sham 59.0 ± 20 mm) ($t_{(13)} = 0.494$, $p = 0.629$, $BF_{10} = 0.300$) and craving for sweet foods (active 38.8 ± 20.1 mm, sham 39.2 ± 20.1 mm) ($t_{(13)} = 0.512$, $p = 0.617$, $BF_{10} = 0.303$) were not significantly different between active and sham conditions (Fig. 3). Craving for savoury foods approached significance (active 45.3 ± 17.9 mm, sham 49.4 ± 20.6 mm) ($t_{(13)} = 2.128$, $p = 0.053$), suggesting reduced craving for savoury foods following active protocols, but the effect was only supported by anecdotal evidence in favour of the alternative hypothesis ($BF_{10} = 1.505$). However, positive mood scores were significantly lower following active (47.1 ± 10.1 mm) compared with sham tDCS (51.5 ± 11.0 mm) ($z = -2.271$ 13.000, $p = 0.025$, $BF_{10} = 5.023$).

3.6. Responses to tDCS

Stimulation was successfully delivered across all 34 sessions, with mean impedance levels of 8 ± 5 kΩ at the start of stimulation. Participants experienced similar sensations following both active and sham conditions (Table 5), with only itching differing between sessions ($z = 2.366$, $p = 0.011$, $BF_{10} = 4.718$). There were no differences in the severity of adverse events across active and sham protocols (Table 5). Despite the lack of difference in presence and severity of adverse events, participant blinding was not successfully achieved in the present study with 70.6% of participants able to identify the correct order of tDCS conditions. Additionally, researcher blinding was not upheld, with correct guess of 75.0%. Although both participants and the researcher were able to correctly identify the active tDCS condition, confidence scores were moderate for both participants (5.3 ± 2.5 AU) and the researcher (4.3 ± 2.7 AU).

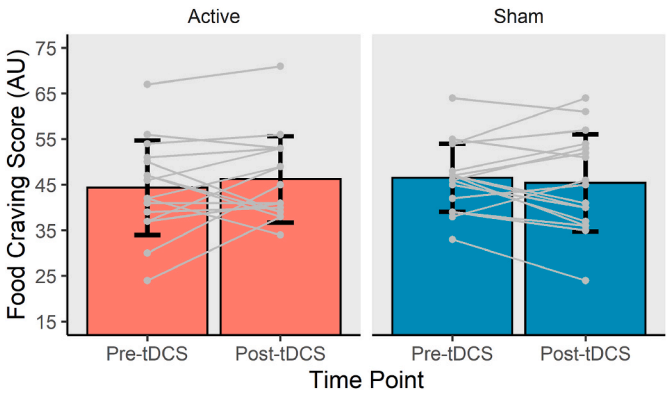


Fig. 2. Mean ± SD food craving scores (n = 17).

4. Discussion

The present study aimed to identify the effects of tDCS applied over the right DLPFC on eating-related measures in those with mild-to-moderate binge-type behaviour. While the study applied those parameters that appear to produce the most consistent modulation of eating behaviour (Beaumont et al., 2022a; Hall et al., 2017; Lowe et al., 2017), and focussed on a population with eating behaviour traits suggesting susceptibility to overconsumption (Beaumont et al., 2022b), a general lack of significant effects were observed when comparing active and sham tDCS conditions.

While there are limited significant differences observed across the data when analysed using frequentist statistics, Bayesian analyses provides support for an effect with moderate-to-extreme evidence in favour of the alternative hypothesis (i.e., supporting the hypothesis that tDCS can modulate eating-related measures) when including post-meal data in the analyses. When considering mean scores between active and sham protocols, there does appear to be an effect of active tDCS across some measures. For example, while post-tDCS scores are numerically close across measures of hunger, fullness and prospective consumption, post-meal scores suggest active protocols can suppress hunger and prospective consumption and enhance fullness sensations to a greater degree than sham tDCS. Such effects may explain the large Bayes factors observed for these comparisons. It should be noted, however, that similar patterns are not observed across many of the variables included in the original study hypothesis; namely, food craving, desire to eat and food reward scores. Therefore, tDCS shows some promise as an intervention in a few measures but we suggest these data should be interpreted with caution when contextualised against the wider findings.

Pre- and post-tDCS data from the present study largely align with those reported in our prior work (Beaumont et al., 2021) as well as other studies (Amo Usanos et al., 2020; Chen et al., 2019; Fassini et al., 2020; Grundeis et al., 2017). For the present work, there are limited significant effects in line with the study hypotheses, and active tDCS appeared to increase hunger, and the explicit liking and wanting for sweet foods. These effects were in the opposite direction than hypothesised. While previous studies have demonstrated reduced craving or implicit wanting for sweet foods (Burgess et al., 2016; Carvalho et al., 2019; Goldman et al., 2011), these effects have not been consistent with reduction in the consumption of high-fat and sweet foods (To et al., 2018). There is evidence to suggest that those with binge-type behaviour display heightened liking and wanting for sweet foods, and particularly HFSW foods (Dalton & Finlayson, 2014; Finlayson & Dalton, 2012a). While explicit liking for HFSW food images was significantly lower at baseline in the active session, a reflection of the heightened hunger observed in the sham session, scores were comparable post-tDCS under both active and sham stimulation.

While the present work is novel in the comparison between fasted and fed states, prior work has explored the effects of tDCS on these states independently. As previously discussed by our group (Beaumont et al., 2022b), fasting conditions vary greatly across studies and range from 2 to 7 h with or without rigorous control measures (Bravo et al., 2016; Heinitz et al., 2017; Kekic et al., 2014, 2017; Montenegro et al., 2011; Ray et al., 2017, 2019). These studies have demonstrated significant differences in eating-related measures following tDCS, although no consistent effects in support of tDCS are observed. When exploring the effects of tDCS in the fed state, Schroeder et al. (2023) failed to identify an effect on measures of food craving, hunger and thirst in a group of female participants with restrained and unrestrained eating following a

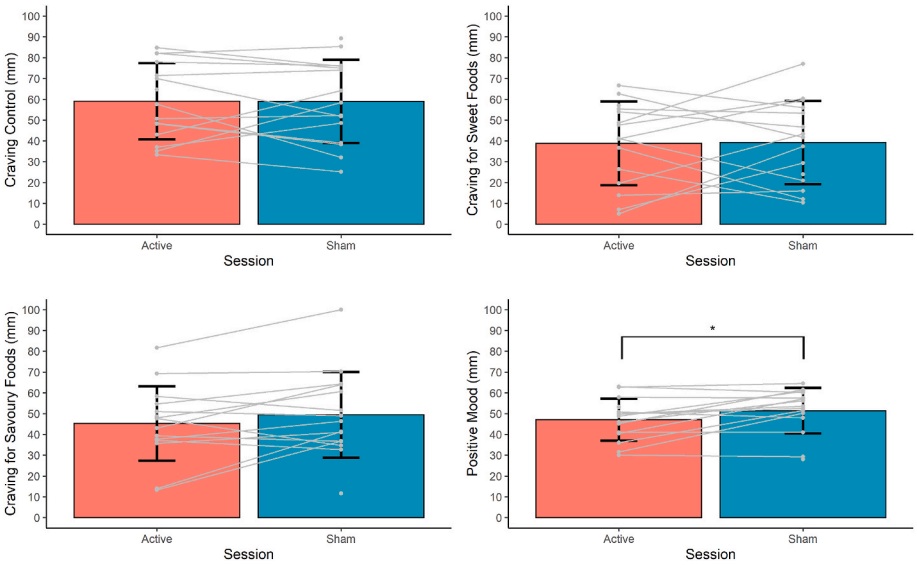


Fig. 3. Comparison of CoEQ (24-h version) scores following active and sham tDCS (n = 17). *p < 0.05.

Table 5
Frequency and severity of adverse events immediately post-stimulation (n = 17).

Sensation	Frequency (n)				Severity score[b] (mean ± SD)			
	Active tDCS	Sham tDCS	p	BF_{10}	Active tDCS	Sham tDCS	p	BF_{10}
Headache	1 (6%)	3 (18%)	0.424	0.354	1.0 ± 0.0	1.0 ± 0.0	0.424	0.371
Neck pain	1 (6%)	1 (6%)	1.000	0.342	1.0 ± 0.0	1.0 ± 0.0	0.424	0.358
Scalp pain	1 (6%)	1 (6%)	1.000	0.310	1.0 ± 0.0	2.0 ± 0.0	1.000	0.321
Tingling	8 (47%)	5 (29%)	0.233	0.451	1.5 ± 0.7	1.6 ± 0.8	0.386	0.409
Itching	10 (59%)	3 (18%)	0.011	4.718	1.4 ± 0.7	2.0 ± 0.8	0.081	1.170
Burning sensation	5 (29%)	2 (12%)	0.233	0.485	1.0 ± 0.0	2.0 ± 1.0	0.824	0.315
Skin redness	4 (24%)	0 (0%)	–	–	1.0 ± 0.0	–	–	–
Sleepiness	8 (47%)	12 (71%)	0.129	0.695	1.8 ± 0.7	1.6 ± 0.6	0.120	0.781
Trouble concentrating	4 (24%)	6 (35%)	0.530	0.322	2.3 ± 0.4	1.2 ± 0.4	0.708	0.271
Acute mood change	1 (6%)	2 (12%)	1.000	0.375	2.0 ± 0.0	1.5 ± 0.5	1.000	0.367
Other	0 (0%)	1 (6%)[a]	–	–	–	1.0 ± 0.0	–	–

[a] Participant reported a pulsating sensation.
[b] Scored on a four-point scale; 0 = not present, 1 = mild, 2 = moderate, 3 = severe.

standardised breakfast meal. In the fasted state, individuals experience heightened hedonic response to foods and related cues (Castellanos et al., 2009; Goldstone et al., 2009) and so eating-related behaviours may be more amenable under these conditions. Certainly, there appears to be differences in DLPFC activity when exposed to food cues in the fasted versus fed state (Charbonnier et al., 2018). While no significant effects are observed in the present study, post-meal mean scores and change from pre-meal scores are comparable across active and sham conditions.

The present findings suggest active tDCS is unable to moderate eating-related scores in females with mild-to-moderate binge eating behaviour. In combination with the above, this may indicate the need for further consideration of target populations. It is possible that the participants recruited to this study, while displaying eating behaviour traits suggesting susceptibility to overconsumption, did not display the full trait profile associated with modulatory impact of tDCS. The change in hunger scores in the present work are similar to those reported by Marron et al. (2019), who applied similar parameters as those in the present study, albeit focussing on left DLPFC stimulation. Marron et al. also recruited "healthy" populations, who are unlikely to respond to the modulatory effects of tDCS (Beaumont et al., 2022b). The findings of Burgess et al. (2016) suggest active tDCS is able to reduce food craving and consumption compared with sham protocols, and differ to the present study. In reconciling the discrepancies, the participants in the study by Burgess et al. (2016) had a BES score of 27 ± 6 AU, so were at the clinically-relevant end of the scale, whereas the present study recruited those with sub-clinical binge eating behaviour and a lower BES score (21 ± 4 AU).

As such, the present study was limited in terms of focussing on those with non-clinically relevant binge eating behaviour. This work was constrained to institutional limits on studying participants who were categorised as healthy individuals (i.e., non-clinical populations). As discussed, several studies have demonstrated that only those with BED appear to be responsive to tDCS, whereas those with frank obesity are not (Burgess et al., 2016; Max et al., 2020; Ray et al., 2017). It could be that the participants recruited to the present study fall within this latter group, or do not display sufficiently predominant trait behaviours to be considered "responsive" to tDCS. While the BES is a psychometrically valid indicator of binge-type behaviour that is widely used in research (Celio et al., 2004; Gormally et al., 1982; Grupski et al., 2013), the BES is not intended as a clinical diagnostic tool (Cotter & Kelly, 2016) and does not measure all of the diagnostic criteria for BED (American Psychiatric Association, 2013). Further exploration of the potential eating behaviour trait-dependent effect of tDCS is warranted to directly compare the efficacy in clinical and sub-clinical populations. In line with the evidence from prior studies, it may be that only those displaying clinically-relevant behaviours are responsive to the modulatory influence of tDCS (Amo Usanos et al., 2020; Bravo et al., 2016; Burgess et al., 2016; Chen et al., 2019; Fassini et al., 2020; Grundeis et al., 2017; Kekic et al., 2017; Max et al., 2020; Ray et al., 2017).

It is important to consider whether the lack of significant effects is the result of small sample size which can lead to a lack of statistical power to detect such significant differences. An *a priori* sample size calculation was completed for the present study, which was based on the findings for food craving and explicit wanting scores across a number of recently published studies (Fregni et al., 2008; Goldman et al., 2011; Kekic et al., 2014; Ljubisavljevic et al., 2016; Ray et al., 2017), and is aligned with the sample size from previous work (Beaumont et al., 2021; Goldman et al., 2011; Kekic et al., 2014; Ray et al., 2017). Nevertheless, power calculation conducted *a posteriori* suggest only moderate power was achieved (mean 0.54 ± 0.36; range 0.06–1.00). When considering the sample size required to identify a significant effect across measures, based on the effect sizes for pre- and post-tDCS data, this is considerably higher than the number of recruited participants (mean 431 ± 755 individuals), with minimum sample size ranging from 6 to 1963 across variables. Of note, based on these calculations sufficient sample size and power were achieved for appetite VAS measures (achieved power = 0.80 ± 0.18).

An important consideration for the present data, regardless of statistical comparisons, is that change in mean scores for some measures suggests active tDCS altered eating-related measure in the direction opposite to the original hypothesis. For example, it was hypothesised that active protocols would reduce the desire to eat, but hunger, prospective consumption and desire to eat VAS scores all increased following active versus sham tDCS. Indeed, the explicit liking and wanting for HFSW foods significantly increased following active tDCS. This raises several questions around the assumptions made for the effects of anodal versus cathodal tDCS (Jacobson et al., 2012). Although anodal tDCS appears to produce the most consistent reduction in eating-related scores (Beaumont et al., 2022a), efficacy of the assumed anodal-excite/cathodal-inhibit dichotomy has been disputed (Bestmann et al., 2015; Fertonani & Miniussi, 2016). Only a small proportion of studies have directly compared the effects of anodal and cathodal tDCS on eating behaviours and while early studies suggest clear anodal-excite/cathodal-inhibit effects this in not consistent across all studies (Carvalho et al., 2019; Fregni et al., 2008; Gluck et al., 2015; Grundeis et al., 2017; Kekic et al., 2017; Vicario et al., 2020). Further comparison of these effects is warranted across different populations, in conjunction with the use of brain imaging tools to clearly demonstrate the impact of tDCS on brain activity under these parameters.

The lack of significant differences across craving control and craving for sweet and savoury food measures of the CoEQ is not surprising. It has been suggested that the effects of tDCS are likely only to be present until up to 90 min post-stimulation (Nitsche & Paulus, 2001). The 24-h version of the CoEQ was completed at the end of the test visit days, which falls outside of this window. As such, the modulatory effects are likely to have diminished by the time participants complete this questionnaire. In line with this, these effects are only supported by anecdotal evidence as indicated by Bayes factors.

As an adjunct to the present study, it may be possible to promote learning and changes in eating behaviour using online (i.e., performed at the same time as tDCS) food-based cognitive training tasks (Miniussi et al., 2013; Nitsche & Paulus, 2001). Certainly, under similar tDCS parameters as used in the present study, Max et al. (2020) found faster latencies of correct anti-saccades in an online food-modified task in those with BED. However, there is currently only limited evidence to support the use of online tasks and further consideration for the impact these may have on eating-related measures following tDCS is needed. The use of such online tasks may impact the expected polarity-dependent effects of tDCS (Thair et al., 2017) and as such careful consideration of the applied parameters is needed.

Finally, despite following the same protocol as our prior study (Beaumont et al., 2021) participant blinding was not upheld in the present study and a large percentage of participants were able to distinguish between active and sham protocols. While confidence scores did not suggest participants were sure of the condition order, qualitative statements collected whilst measuring blinding efficacy suggest that differences in sensations of itching and tingling were the reason for participants guessing correctly. Similarly, while researcher blinding was not upheld, confidence scores did not suggest the researcher was sure of the order of conditions, and qualitative statements were mainly around the sensations experienced by participants. These findings question the previous assumption that sham protocols are an effective blinding tool (Brunoni et al., 2011; Gandiga et al., 2006; Nikolin et al., 2018), and instead provides further evidence that blinding cannot be upheld where cutaneous sensations are more pronounced (O'Connell et al., 2012).

5. Conclusion

The present study looked to identify the impact of offline tDCS in those with mild-to-moderate binge-type behaviour and is the first study to compare the effects of tDCS in the fasted and fed states. Despite evidence of a potential eating behaviour trait-dependent effect of tDCS (Beaumont et al., 2022b), the present study did not demonstrate clear support for this. A potential explanation may be due to the focus on a non-clinical population with only mild-to-moderate binge eating behaviour, while prior studies demonstrating an effect often focus on clinical populations (e.g., BED). As such, the present participants' may not have met the threshold required to see the modulatory effects of tDCS. This may also reflect the variability in response to stimulation and future work should aim to introduce brain imaging techniques so an understanding of the impact of applied parameters can be achieved, and further consider individuals who may be responsive to the modulatory effects of tDCS.

Author contributions

Jordan Beaumont: Conceptualisation, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review and editing, Visualisation, Project administration. **Michelle Dalton**: Conceptualisation, Methodology, Software, Formal analysis, Resources, Data curation, Writing – review and editing. **Danielle Davis**: Conceptualisation, Methodology, Resources, Writing – review and editing, Supervision. **Graham Finlayson**: Software, Formal analysis, Resources, Writing – review and editing. **Alexander Nowicky**: Methodology, Writing – review and editing. **Mark Russell**: Methodology, Writing – review and editing. **Martin Barwood**: Conceptualisation, Methodology, Validation, Resources, Writing – original draft, Writing – review and editing, Supervision.

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Ethics statement

We confirm the activities described in the above named manuscript adhered to the ethical standards outlined in the Declaration of Helsinki. The study was reviewed by the School of Social and Health Sciences Ethics Committee at Leeds Trinity University (ethics code: SSHS-2019-023) and the School of Psychology Research Ethics Committee at the University of Leeds (ethics code: PSC-880). Prior to data collection, all interested individuals were provided an information sheet and participants completed informed consent procedures.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.appet.2023.106997.

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