

The effect of transcranial direct current stimulation (tDCS) on food craving, reward and appetite in a healthy population.

BEAUMONT, Jordan <<http://orcid.org/0000-0002-9861-3379>>, DAVIS, Danielle, DALTON, Michelle, NOWICKY, Alexander, RUSSELL, Mark <<http://orcid.org/0000-0002-7305-1090>> and BARWOOD, Martin J

Available from Sheffield Hallam University Research Archive (SHURA) at:

<http://shura.shu.ac.uk/31270/>

This document is the author deposited version. You are advised to consult the publisher's version if you wish to cite from it.

Published version

BEAUMONT, Jordan, DAVIS, Danielle, DALTON, Michelle, NOWICKY, Alexander, RUSSELL, Mark and BARWOOD, Martin J (2021). The effect of transcranial direct current stimulation (tDCS) on food craving, reward and appetite in a healthy population. *Appetite*, 157: 105004.

Copyright and re-use policy

See <http://shura.shu.ac.uk/information.html>

1 **The effect of transcranial direct current stimulation (tDCS) on food craving, reward**
2 **and appetite in a healthy population.**

3

4 Jordan D. Beaumont^{a,*}, Danielle Davis^a, Michelle Dalton^a, Alexander Nowicky^b, Mark
5 Russell^a and Martin J. Barwood^a

6

7 ^a*School of Social and Health Sciences, Leeds Trinity University, Leeds, LS18 5HD, UK*

8 ^b*Centre for Cognitive Neuroscience, Department of Clinical Sciences, College of Health and*
9 *Life Sciences, Brunel University London, Uxbridge, UB8 3PH, UK*

10 **Corresponding author, email: j.beaumont@leedstrinity.ac.uk*

11

12 **ABSTRACT**

13 The ability to control hedonic appetite is associated with executive functioning originating in
14 the prefrontal cortex (PFC). The rewarding components of food can override homeostatic
15 mechanisms, potentiating obesogenic behaviours. Indeed, those susceptible to
16 overconsumption appear to have PFC hypo-activation. Transcranial direct current
17 stimulation (tDCS) over the dorsolateral PFC (DLPFC) has been shown to reduce food
18 craving and consumption, potentially via attenuating this reward response. We examined the
19 effects of stimulation on food reward and craving using a healthy-weight cohort. This study is
20 amongst the first to explore the effects of tDCS on explicit and implicit components of reward
21 for different food categories. Twenty-one healthy-weight participants (24 ± 7 years, $22.8 \pm$
22 $2.3 \text{ kg}\cdot\text{m}^{-2}$) completed two sessions involving double-blind, randomised and counterbalanced
23 anodal or sham tDCS over the right DLPFC, at 2 milliampere for 20 minutes. Food craving
24 (Food Craving Questionnaire-State), reward (Leeds Food Preference Questionnaire), and
25 subjective appetite (100 mm visual analogue scales) were measured pre- and post-tDCS.
26 Eating behaviour trait susceptibility was assessed using the Three Factor Eating
27 Questionnaire-Short Form, Control of Eating Questionnaire, and Food Craving
28 Questionnaire-Trait-reduced. Stimulation did not alter food craving, reward or appetite in
29 healthy-weight participants who displayed low susceptibility to overconsumption, with low
30 trait craving, good craving control, and low uncontrolled eating and emotional eating
31 behaviour. Implicit and explicit reward were reliable measures of hedonic appetite,
32 suggesting these are robust targets for future tDCS research. These findings suggest that
33 applying tDCS over the DLPFC does not change food reward response in individuals not at
34 risk for overconsumption, and future work should focus on those at risk of overconsumption
35 who may be more responsive to the effects of tDCS on hedonic appetite.

36

37 **KEYWORDS**

38 Appetite control; Dorsolateral prefrontal cortex; Neuromodulation; Food craving; Food
39 reward

40

41 **HIGHLIGHTS**

- 42 • We consider the effects of tDCS on implicit and explicit reward using a validated task
- 43 • High reliability in reward measures suggest a robust target for future tDCS studies
- 44 • Previously findings are limited by high variation within food-related variables
- 45 • Effects of tDCS may be dependent on participant eating behaviour traits
- 46 • Future work should screen participants using validated psychometric questionnaires

47 1. INTRODUCTION

48 Obesity is a global health epidemic that affects more than 650 million adults worldwide, and
49 is associated with an increased risk of developing many other health conditions (World
50 Health Organisation, 2020). The aetiology of obesity involves a complex relationship
51 between behavioural, biological and environmental factors, contributing to the dysregulation
52 of energy balance (Hill, 2006). Hedonic appetite can potentiate this dysregulation, with the
53 rewarding components of food overriding homeostatic mechanisms (Boswell & Kober, 2016;
54 Kober & Boswell, 2018). The ability to control hedonic appetite is associated with executive
55 functioning, which originate in the prefrontal cortex (PFC) and inhibit impulsive actions in
56 favour of goal-directed behaviours (Joseph, Alonso-Alonso, Bond, Pascual-Leone, &
57 Blackburn, 2011). Altered PFC activity in response to food stimuli has been identified in
58 individuals with obesity, especially those displaying binge eating symptoms (Boeka &
59 Lokken, 2011; Karhunen, et al., 2000). It is proposed that a reduction of activity in the right
60 dorsolateral PFC (DLPFC) could facilitate obesogenic behaviours through poor appetite
61 control (Alonso-Alonso & Pascual-Leone, 2007). Indeed, dysregulation of the DLPFC has
62 been linked with greater impulsive behaviours, often leading to overconsumption (Gluck,
63 Viswanath, & Stinson, 2017). Increasing DLPFC activity may improve the ability to control
64 hedonic appetite, providing a novel paradigm in the treatment of obesity (Alonso-Alonso,
65 2013).

66

67 The modulation of cortical activity is possible through the use of non-invasive brain
68 stimulation techniques, such as transcranial direct current stimulation (tDCS). This form of
69 stimulation involves the application of a weak electrical current, typically up to 2 milliamperere
70 (mA), to a specific region of the brain via two electrodes that are placed over the scalp
71 (Nitsche & Paulus, 2000). The current is emitted from a battery-powered device, where it is
72 delivered to the brain through an anode electrode and returns to the device through a
73 cathode electrode. The current intensity is not sufficient to cause neuronal firing, but results
74 in the polarity-dependent subthreshold modulation of resting membrane potentials (Filmer,

75 Dux, & Mattingley, 2014; Jamil & Nitsche, 2017). Although the exact mechanisms are not
76 fully understood, it appears the current inhibits neurotransmitters at the synapse; the anode
77 is associated with the inhibition of gamma-aminobutyric acid (GABA) whereas the cathode is
78 associated with the inhibition of glutamate (Filmer, et al., 2014; Stagg, Antal, & Nitsche,
79 2018). The inhibition of these neurotransmitters increases or decreases the likelihood of
80 spontaneous neuronal firing, respectively. In addition to these acute effects, tDCS also
81 appears to elicit changes in cortical activity beyond the stimulation duration. For example, in
82 an early study by Nitsche and Paulus (2001), anodal tDCS lasting 13 minutes resulted in
83 greater activity in the motor cortex for up to 90 minutes post-stimulation.

84

85 When identifying the effects of tDCS on hedonic appetite, many studies have focussed on
86 measuring state food craving. The first study to identify the impact of tDCS on hedonic
87 appetite compared anodal stimulation to the left and right DLPFC in 21 healthy-weight
88 individuals with frequent food cravings, defined as experiencing 3 or more strong urges to
89 consume high-calorie foods per day (Fregni, et al., 2008). When applying 2 mA stimulation
90 for 20 minutes, a significant reduction in food craving was observed following tDCS over the
91 right DLPFC, but not when applied to the left hemisphere. This reduction in state craving
92 score was replicated in a second study that used the same stimulation parameters and
93 recruited a similar participant cohort ($n = 19$) (Goldman, et al., 2011).

94

95 In two recent publications, Burgess and colleagues highlight a potential eating behaviour
96 trait-dependent effect of tDCS (Burgess, et al., 2016; Ray, et al., 2017). Thirty participants
97 who were obese and met the diagnostic criteria for binge eating disorder (BED) underwent
98 20 minutes of 2 mA tDCS to the right DLPFC, which resulted in a significant decrease in
99 state food craving and in-laboratory food consumption (Burgess, et al., 2016). In contrast,
100 these effects were not significant when this protocol was replicated in 18 participants with
101 frank obesity (i.e. non-binge eating) (Ray, et al., 2017). This suggests that the effects of
102 tDCS may be dependent on individual variation in the level of susceptibility to reward-driven

103 overconsumption. Consistent with this, previous research has demonstrated that individuals
104 with BED are hyper-responsive to the rewarding aspects of food (Davis, 2013; Davis, et al.,
105 2009). The estimated prevalence of BED in the general population ranges from 0.7 – 3.0%,
106 and is commonly comorbid with overweight and obesity (Kessler, et al., 2013). Recurrent
107 episodes of binge eating behaviour are estimated to occur in 10 – 20% of individuals who
108 are healthy weight, overweight or obese, and constitutes a trait that can be assessed
109 psychometrically and applied to a non-clinical population. Similar to findings in individuals
110 with BED, individuals with eating behaviour trait susceptibility to overconsume (i.e. binge
111 eating and emotional eating) have been found to be hyper-responsive to the rewarding
112 aspects of food (Dalton, Blundell, & Finlayson, 2013a). Therefore, including validated
113 measures of food reward and eating behaviour trait susceptibility may be important when
114 considering the effect of tDCS on food consumption, reward and craving. To date, no study
115 has identified the effects of tDCS on implicit and explicit components of reward across
116 different food categories.

117

118 Although there are many promising findings, not all studies have found an effect of tDCS on
119 measures of hedonic appetite. This may be due to the inconsistent application of stimulation
120 parameters (e.g. variation in target electrode placement and current intensity), inadequate
121 experimental blinding, and large variation in experimental measures (Hall, Vincent, &
122 Burhan, 2018; Tremblay, et al., 2014). The most consistently used measure of hedonic
123 appetite in tDCS research is food craving, which is commonly assessed using the Food
124 Craving Questionnaire-State (FCQ-S) (Cepeda-Benito, Gleaves, Williams, & Erath, 2000).
125 Although significant effects of tDCS on food craving have been identified (Fregni, et al.,
126 2008; Goldman, et al., 2011), this has not been consistently shown (Georgii, Goldhofer,
127 Meule, Richard, & Blechert, 2017; Sedgmond, et al., 2019). Across studies there is large
128 variation in state food craving scores, ranging from 0.40% to 41.67% following the active
129 condition (Fregni, et al., 2008; Goldman, et al., 2011; Kekic, et al., 2014; Ljubisavljevic,
130 Maxood, Bjekic, Oommen, & Nagelkerke, 2016), which may be due to the poor reliability of

131 these measures. Developmental publications of the FCQ-S suggest low-to-moderate
132 reliability ($r = 0.39 - 0.56$) (Cepeda-Benito, et al., 2000; Meule, Teran, et al., 2014).
133 Measures of food consumption have also been utilised, primarily using *ad libitum* buffets of
134 highly palatable foods (Burgess, et al., 2016; Georgii, et al., 2017; Gluck, et al., 2015; Ray,
135 et al., 2017; Sedgmond, et al., 2019). Although greater craving control is associated with
136 improved weight loss outcomes (Dalton, et al., 2017), the effects of tDCS on craving and
137 consumption are not correlated (Burgess, et al., 2016), suggesting other targets are required
138 to validate tDCS as an intervention to alter eating behaviour. Food reward plays a more
139 pivotal role in the dysregulation of energy balance (Boswell & Kober, 2016; Kober & Boswell,
140 2018). Therefore, it is important to look beyond the measure of food craving and identify the
141 role of tDCS in modulating food reward.

142

143 The present study examined how measures of food craving, reward and appetite would
144 change following the inducement of hyper-activity of the right DLPFC through tDCS in a
145 healthy-weight cohort. We hypothesised stimulation would reduce state food craving and
146 subjective appetite, based on previous findings utilising healthy participant groups (Fregni, et
147 al., 2008; Goldman, et al., 2011; Kekic, et al., 2014; Lapenta, Sierve, de Macedo, Fregni, &
148 Boggio, 2014). We also hypothesised that participants' preference for and perceived
149 rewarding value of high-fat and sweet foods would be diminished following anodal tDCS. We
150 also looked to establish the reliability of these measures, including both implicit and explicit
151 components of reward, prior to tDCS with a view to establishing the viability of their future
152 use in our research.

153

154 **2. METHODS**

155 **2.1 Participants**

156 The study was approved by an institutional ethics committee, and all participants provided
157 written informed consent. Sample size was determined using G*Power 3.0.10 (Faul,
158 Erdfelder, Lang, & Buchner, 2007). An effect size f of 0.33 was based on mean percentage

159 difference from baseline in food craving scores following single session tDCS (mean
160 difference between conditions $-22.22 \pm 33.68\%$) (Fregni, et al., 2008; Goldman, et al., 2011;
161 Kekic, et al., 2014; Ljubisavljevic, et al., 2016). Using α error probability of 0.05, 1 group with
162 2 measurements, a correlation among repeated measures equal to 0.5, and non-sphericity
163 correlation ϵ of 1, sample size calculations determined a minimum sample size of 21, with
164 actual power of 0.82, was required. Twenty-one participants (24 ± 7 years, 22.8 ± 2.3 kg·m⁻²)
165 were recruited via email and poster advertisements. Interested individuals were initially
166 screened with an online questionnaire. Eligible participants were male or female between 18
167 and 60 years of age who presented with a body mass index (BMI) between 18.5 and 24.9.
168 All participants were free of neurological, cardiovascular, metabolic and joint disease, and
169 potential participants were excluded if they presented with low mood or depressive
170 symptoms, as indicated using the Centre for Epidemiologic Studies Short Depression Scale
171 (CESD-10) (Andresen, Malmgren, Carter, & Patrick, 1994; Radloff, 1977). Female
172 participants who were pregnant or wishing to conceive were also excluded from the study.
173 Participants were naïve to tDCS protocols, non-smokers and were not recreational drug
174 users or taking any medications at the time of data collection.

175

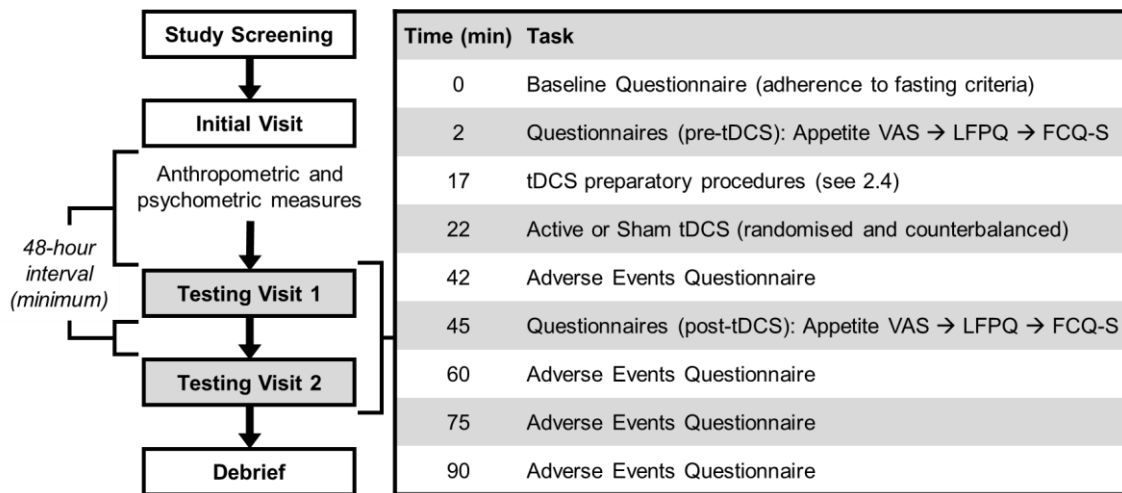
176 **2.2 Experimental Design**

177 The study utilised a double-blind, within-participant, repeated measures design. Participants
178 attended the laboratory on three separate occasions (Figure 1). During the first visit,
179 participants completed a series of psychometric questionnaires, and height and body
180 composition were measured. Visits 2 and 3 were experimental trials where all participants
181 received either active or sham tDCS in a randomised and counterbalanced order.
182 Randomisation was determined using a permuted block paradigm and completed by an
183 independent party. The participants and researcher conducting stimulation were blind to the
184 tDCS condition, adhering to a double-blind design, which was maintained using a pin-
185 protected device. All sessions were scheduled at the same time of day within-subject,
186 occurring between 09:00 and 15:00, and with a minimum interval of 48 hours between

187 sessions to prevent any residual effects of stimulation (Alonzo, Brassil, Taylor, Martin, & Loo,
 188 2012).

189

190



191

192 **Figure 1** Study Procedure

193 FCQ-S, Food Craving Questionnaire-State; LFPQ, Leeds Food Preference Questionnaire;
 194 tDCS, transcranial direct current stimulation; VAS, visual analogue scales.

195

196 **2.3 Procedure**

197 Participants were required to fast for a minimum of 4 hours prior to each visit, where they
 198 were asked to refrain from consuming any food or drink other than water. In addition, they
 199 were asked to refrain from consuming products containing caffeine and alcohol in the 12 or
 200 24 hours prior to each visit, respectively. Adherence to this fasting criteria was self-reported
 201 at the start of each visit. On arrival at the laboratory, participants were instructed to turn off
 202 their mobile phones and remove any metallic objects from their person in adherence with our
 203 tDCS protocol.

204

205 During visit 1, participants completed the Three Factor Eating Questionnaire-Short Form
 206 (TFEQ-r18), Control of Eating Questionnaire (CoEQ), and Food Craving Questionnaire-Trait-
 207 reduced (FCQ-T-r); see 2.5.1. Height was measured using a portable stadiometer (SECA

208 Limited, Birmingham, UK) to the nearest mm. Measurements were taken following
209 inhalation, with the participant standing straight, their back to the rule, and their eyeline level
210 with ear canal. Body composition, including weight and BMI, was assessed using a Tanita
211 BC-418MA analyser (Tanita Europe B.V., Amsterdam). Weight was measured to the nearest
212 0.1 kg, and body fat percentage to the nearest 0.1%. Participants were then shown the food
213 images used in the Leeds Food Preference Questionnaire (LFPQ; see 2.5.4), and their
214 familiarity and acceptance of each food item was assessed. Any food items that were
215 unfamiliar or had low acceptance (i.e. disliked or not consumed in the normal diet) were
216 substituted with images from a database of additional items with similar nutritional and
217 sensory properties (Oustric, et al., 2020).

218

219 During visits 2 and 3, participants completed a series of questionnaires immediately pre-
220 tDCS (Figure 1). These included appetite visual analogue scales (VAS), the FCQ-S and the
221 LFPQ; see 2.5. Each participant then underwent 20 minutes of active or sham tDCS.
222 Questionnaires were then repeated immediately post-stimulation. Visits 2 and 3 were
223 identical, apart from the stimulation condition. At the end of visit 3, participants were
224 debriefed. They were informed of the sham stimulation condition and were asked whether
225 they were able to differentiate between the active and sham conditions, and in which visit
226 they believe active tDCS was delivered.

227

228 **2.4 Stimulation Protocol**

229 Stimulation was delivered using the HDCstim direct current stimulator (Newronika s.r.l.,
230 Milan, Italy) by a trained researcher. Anodal stimulation was used to target the right DLPFC,
231 in accordance with the International Standards for Electroencephalography 10-20 system
232 (Klem, Lüders, Jasper, & Elger, 1999). A 25 cm² anode electrode was placed over the frontal
233 area 4 (F4) and a 51 cm² cathode electrode placed over occipital zero point (Oz). Cathode
234 placement over the Oz reduces the impact of associated inhibitory effects on study
235 measures (Bestmann, de Berker, & Bonaiuto, 2015; Galetta, 2017), and decreases the

236 likelihood of current shunting across the scalp (Rush & Driscoll, 1968). Rubber electrodes
237 were housed in sponge pads, pre-soaked in 0.9% sodium chloride. A constant current of 2
238 mA was delivered through the anode electrode, culminating in a current density of 0.08
239 mA·cm⁻². The current was ramped up over a 30-second period, and active tDCS was then
240 delivered for 20 minutes, with a 30-second ramp down. Stimulation was delivered offline (i.e.
241 no task was performed during tDCS), and participants were instructed to remain seated,
242 relaxed and awake. Sham stimulation involved the same setup as active tDCS, but the
243 current was only delivered for 36 seconds (3% active tDCS duration). This is associated with
244 similar sensations (e.g. itching, tingling) (Brunoni, et al., 2011; Nikolin, Huggins, Martin,
245 Alonzo, & Loo, 2018), but has a limited neuromodulatory effect (Gandiga, Hummel, &
246 Cohen, 2006).

247

248 The effectiveness of sham as a blinding technique was assessed during debrief. Impedance
249 was measured at the start of stimulation, and periodically checked thereafter. It is
250 recommended that impedance should remain below 5 kilo-ohm (kΩ) (DaSilva, Volz, Bikson,
251 & Fregni, 2011; Thair, Holloway, Newport, & Smith, 2017). The occurrence of sensations
252 and adverse events were measured using a standardised questionnaire (Brunoni, et al.,
253 2011) immediately following stimulation and at regular intervals for a minimum of 45 minutes,
254 in accordance with our standardised procedure.

255

256 **2.5 Measurements**

257 *2.5.1 Psychometric Questionnaires*

258 A series of psychometric questionnaires were used to assess eating behaviour traits of
259 participants in the screening session (Figure 1). The TFEQ-r18 (Karlsson, Persson,
260 Sjöström, & Sullivan, 2000) measures three subscales of eating behaviour; cognitive
261 restraint, uncontrolled eating, and emotional eating. Scores range from 0 to 100 for each
262 subscale, with higher scores indicating a greater presence of problematic eating behaviour.
263 The TFEQ-r18 has good internal validity, with a Cronbach's alpha (α) of 0.82, and

264 comparable construct validity to the full TFEQ ($r = 0.71 - 0.99$) (Karlsson, et al., 2000). The
265 CoEQ (Dalton, Finlayson, Hill, & Blundell, 2015) considers the frequency, intensity and
266 severity of food cravings experienced over the previous 7 days. Items are assessed using
267 100 mm VAS, with scores averaged across items to provide an individual score for craving
268 control, craving for sweet foods, craving for savoury foods, and positive mood. Cronbach's α
269 highlighted acceptable internal validity; craving control $\alpha = 0.88$, craving for sweet foods $\alpha =$
270 0.67 , craving for savoury foods $\alpha = 0.66$, positive mood $\alpha = 0.74$. Finally, general and
271 habitual food cravings were measured using the 15-item FCQ-T-r (Meule, Hermann, &
272 Kübler, 2014). This questionnaire assesses lack of control over eating, emotions
273 experienced before or during food craving and consumption, and guilt from cravings and/or
274 giving in to cravings. A higher score suggests more frequent cravings and a total score
275 greater than 50 highlights clinically relevant trait cravings (Meule, 2018). The FCQ-T-r has
276 high internal validity ($\alpha = 0.94$).

277

278 *2.5.2 Appetite Visual Analogue Scales (VAS)*

279 Four 100 mm VAS were used to assess subjective ratings of appetite (Blundell, et al., 2010),
280 which are sensitive to experimental manipulation and considered reliable and valid
281 measures of subjective appetite (Beechy, Galpern, Petrone, & Das, 2012). Scales measured
282 hunger ("*How hungry do you feel right now?*"), fullness ("*How full do you feel right now?*"),
283 prospective consumption ("*How much food could you eat right now?*"), and the desire to eat
284 ("*How strong is your desire to eat right now?*"). Scores range from 0 to 100, with higher
285 scores indicating greater prevalence of the appetite measure.

286

287 *2.5.3 Food Craving Questionnaire-State (FCQ-S)*

288 The FCQ-S (Cepeda-Benito, et al., 2000) measures subjective food craving, and is
289 responsive to situational changes (Cepeda-Benito, et al., 2000; Meule, Teran, et al., 2014).
290 This questionnaire assesses the desire to eat, craving for food, and emotional responses to
291 food and consumption over 15 statements. Participants rate each statement on a 5-point

292 scale, where 1 corresponds with “*Strongly disagree*” and 5 corresponds with “*Strongly*
293 *agree*”. Corresponding scores are totalled, with a minimum score of 15 and a maximum of
294 75; higher scores equating to greater momentary craving. Similar to the FCQ-T-r, the state
295 FCQ has good internal validity (Cronbach’s $\alpha = 0.94$) (Cepeda-Benito, et al., 2000).

296

297 *2.5.4 Leeds Food Preference Questionnaire (LFPQ)*

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

312

313 **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

314

315 The LFPQ involves two tasks, where food items are displayed in pairs (forced-choice task)
 316 or individually (single-food task). The forced-choice task measures the implicit wanting for
 317 foods. Participants are required to choose the food they most want to consume “right now”
 318 from two items presented on a computer screen. Scores for implicit wanting are calculated
 319 using a frequency-weighted algorithm, by combining reaction time and the frequency of
 320 choosing or avoiding a food (Dalton & Finlayson, 2014). In the single-food task, participants
 321 are presented with each of the 16 food items individually and asked to rate “*How much do*
 322 *you want some of this food right now?*” and “*How pleasant would it be to taste some of this*
 323 *food right now?*” on 100 mm VAS. This second task measures explicit wanting and liking,
 324 respectively, for each food item. In addition, fat appeal bias (FAB) and taste appeal bias
 325 (TAB) scores are calculated by subtracting mean scores across food groups (e.g. mean low-
 326 fat scores subtracted from mean high-fat scores), and provide scores for explicit liking,
 327 explicit wanting and implicit wanting.

328

329 **2.6 Data Analysis**

330 Mean and standard deviations (SD) were calculated at each time point (pre- and post-
 331 stimulation) under active and sham tDCS conditions. Normality of data were assessed using
 332 Shapiro-Wilks test, and reliability of baseline measures were determined using Pearson’s *r*

333 correlations. The effects of tDCS on FCQ-S and LFPQ scores were evaluated using a 2
334 (condition; active or sham) * 2 (time point; pre-stimulation vs post-stimulation scores)
335 repeated-measures analysis of variance (ANOVA). Post-hoc significant effects were
336 determined using pair-wise comparisons with Bonferroni correction. Although fasting
337 protocols were standardised, significant differences in baseline scores across all appetite
338 VAS measures were found. To control for this difference, scores were transformed to
339 difference from baseline and analysed using a paired-samples t-test. To determine the
340 impact of difference in baseline hunger scores on other test variables, analysis of covariance
341 (ANCOVA) were performed with baseline hunger as a covariate. ANCOVA were additionally
342 performed to control for behaviour trait scores. Adverse events were compared using further
343 paired-samples t-tests. Statistical analyses were performed using SPSS version 21 and 26
344 (IBM, New York, USA). Data are presented as mean \pm SD to an alpha level of 0.05.

345

346 To interpret the null findings and assess the strength of evidence, Bayesian statistics were
347 computed using JASP (version 0.13.1; University of Amsterdam). The classification scheme
348 by Lee and Wagenmakers (2013) provides descriptive labels for Bayes factors (BF_{10}), and
349 was used to interpret values. In brief, scores greater than 1 provide evidence in favour of the
350 alternative hypothesis, whereas scores below 1 provide evidence in favour of the null
351 hypothesis. Scores are labelled as anecdotal (score between 1 and 3 or 1 and 0.33),
352 moderate (score between 3 and 10 or 0.33 and 0.10), strong (score between 10 and 30 or
353 0.10 and 0.03), very strong (score between 30 and 100 or 0.03 and 0.01), or extreme (score
354 greater than 100 or lesser than 0.01).

355

356 **3. RESULTS**

357 Participant anthropometric and psychometric characteristics are displayed in
358 Table 2. Participants were weight stable ($\pm 5\%$) for 3 months prior to the study, and displayed
359 “healthy” eating behaviour trait profiles as identified by FCQ-T, CoEQ and TFEQ-r18 scores.
360 Scores for the FCQ-T-r were below the 50-point cut-off for clinically relevant trait craving

361 (Meule, 2018), with CoEQ and TFEQ-r18 scores comparable to healthy-weight individuals in
362 other studies (Anglé, et al., 2009; De Lauzon-Guillain, et al., 2009; Fleurbaix Laventie Ville
363 Sante Study, 2004; Wardle, et al., 2018).

364

365 **Table 2** Mean, standard deviation and range for participant anthropometric and eating behaviour trait characteristics

	Female	Male	All
N	11	10	21
Age (years)	25 ± 9 (19 – 52)	23 ± 4 (20 – 29)	24 ± 7 (19 – 52)
Height (cm)	165 ± 6 (155 – 175)	179 ± 6 (170 – 189)	172 ± 9 (155 – 189)
Weight (kg)	60.1 ± 7.4 (49.6 – 71.4)	76.5 ± 7.1 (66.6 – 88.9)	67.9 ± 11.0 (49.6 – 88.9)
BMI (kg·m ⁻²)	22.0 ± 2.1 (18.5 – 25.0)	23.8 ± 2.2 (20.1 – 27.7*)	22.8 ± 2.3 (18.5 – 27.7*)
Body fat (kg)	16.3 ± 4.3 (10.9 – 23.3)	12.9 ± 4.9 (6.4 – 20.7)	14.7 ± 4.8 (6.4 – 23.3)
Body fat (%)	26.8 ± 4.3 (20.6 – 33.1)	16.6 ± 5.5 (9.2 – 26.0)	21.9 ± 7.1 (9.2 – 33.1)
CESD-10 (AR)	5 ± 3 (0 – 10)	5 ± 4 (0 – 10)	5 ± 3 (0 – 10)
FCQ-T-r (AR)	36 ± 8 (22 – 49)	34 ± 10 (20 – 47)	35 ± 9 (20 – 49)
TFEQ-r18 Cognitive Restraint (AR)	34 ± 19 (5.6 – 61.1)	33 ± 21 (11.1 – 77.8)	40 ± 20 (5.6 – 77.8)
TFEQ-r18 Uncontrolled Eating (AR)	33 ± 11 (7.4 – 44.4)	34 ± 18 (3.7 – 66.7)	33 ± 14 (3.7 – 66.7)
TFEQ-r18 Emotional Eating (AR)	24 ± 24 (0.0 – 66.7)	20 ± 23 (0.0 – 66.7)	22 ± 22 (0 – 66.7)
CoEQ Craving Control (mm)	66 ± 18 (36.0 – 96.2)	68 ± 18 (36.4 – 94.1)	65 ± 18 (36.0 – 96.2)
CoEQ Craving for Sweet Foods (mm)	30 ± 16 (3.0 – 59.7)	28 ± 21 (2.3 – 67.0)	29 ± 18 (2.3 – 67.0)
CoEQ Craving for Savoury Foods (mm)	54 ± 19 (16 – 78)	46 ± 26 (2.0 – 79.3)	51 ± 23 (2.0 – 79.3)
CoEQ Positive Mood (mm)	51 ± 16 (20 – 84)	54 ± 13 (31.0 – 68.3)	52 ± 14 (20 – 84)

* n = 1 with BMI >24.9 due to high fat-free mass (weight 88.9 kg, fat-free mass 74.2 kg, fat mass 14.7 kg / 16.5%).

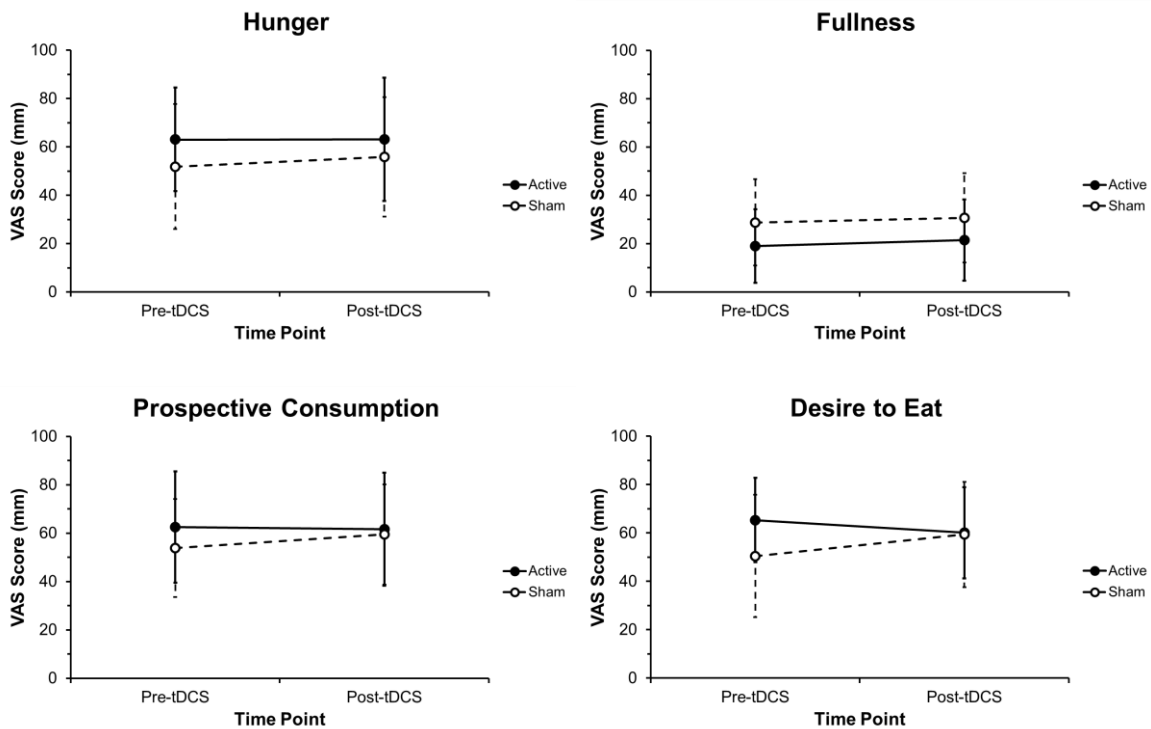
BMI, Body Mass Index; CESD-10, Centre for Epidemiologic Studies Short Depression Scale; FCQ-T-r, Food Craving Questionnaire-Trait reduced form; TFEQ-r18, Three Factor Eating Questionnaire 18-item version; CoEQ, Control of Eating Questionnaire.

367

368 **3.1 Appetite Visual Analogue Scales (VAS)**

369 Baseline hunger scores were significantly higher in the active session (63.1 ± 21.4 mm),
370 when compared to the sham session (51.9 ± 25.8 mm) ($t_{(20)} = 2.567$, $p = 0.018$). Similarly,
371 scores for fullness ($t_{(20)} = 2.925$, $p = 0.008$), prospective consumption ($t_{(20)} = 3.196$, $p =$
372 0.005), and desire to eat ($t_{(20)} = 2.756$, $p = 0.012$) were greater at baseline in the active
373 versus sham session. Baseline hunger scores did not significantly affect fullness,
374 prospective consumption or desire to eat (p 's > 0.05). There were no significant changes in
375 subjective hunger ($t_{(20)} = 0.572$, $p = 0.574$, $BF_{10} = 0.264$), fullness ($t_{(20)} = 0.146$, $p = 0.886$,
376 $BF_{10} = 0.230$), prospective consumption ($t_{(20)} = 0.969$, $p = 0.344$, $BF_{10} = 0.345$), or desire to
377 eat ($t_{(20)} = 1.772$, $p = 0.092$, $BF_{10} = 0.858$) when comparing pre- and post-stimulation in the
378 active and sham tDCS conditions (Figure 2). Bayes factors show moderate evidence in
379 favour of the null hypothesis over the alternative hypothesis for hunger and fullness,
380 whereas prospective consumption and the desire to eat were supported only by anecdotal
381 evidence in favour of the null hypothesis. When controlling for behaviour traits scores, the
382 effects of tDCS on the desire to eat only neared significance ($p = 0.062 - 0.076$), and
383 remained non-significant for other subjective appetite measures (p 's > 0.32).

384



385

386

387 **Figure 2** Mean \pm SD appetite visual analogue scale (VAS) scores prior to and following
 388 tDCS intervention ($n = 21$).

389

390 **3.2 Food Craving Questionnaire-State (FCQ-S)**

391 There were no significant differences in state food craving from pre- to post-stimulation
 392 under active (pre-tDCS 47.2 ± 9.9 AU, post-tDCS 47.8 ± 12.2 AU) or sham conditions (pre-
 393 tDCS 43.8 ± 10.2 AU, post-tDCS 44.9 ± 9.0 AU) ($F_{(1, 19)} = 0.069$, $p = 0.797$). Bayes factor
 394 highlights moderate evidence in favour of the null hypothesis over the alternative hypothesis
 395 ($BF_{10} = 0.272$). In addition, this effect remained non-significant when controlling for baseline
 396 hunger ($F_{(1, 38)} = 0.037$, $p = 0.849$) and behaviour trait scores ($p > 0.74$).

397

398 **3.3 Leeds Food Preference Questionnaire (LFPQ)**

399 Stimulation did not alter measures of implicit or explicit food reward, with the condition * time
 400 point interactions for the liking and wanting of HFSA, LFSA, HFSW and LFSW categories
 401 showing no significant effect ($p > 0.05$) (Table 3), which is supported by moderate-to-strong
 402 evidence in favour of the null hypothesis over the alternative hypothesis ($BF_{10} = 0.041$ –

403 0.168). The interactions remained non-significant when controlling for baseline hunger (p 's >
404 0.10) and behaviour trait scores (p 's > 0.11). In addition, tDCS did not significantly change
405 implicit or explicit TAB, with non-significant condition * time point interactions for explicit
406 liking ($F_{(1, 18)} = 0.079$, $p = 0.782$, $BF_{10} = 0.030$), explicit wanting ($F_{(1, 18)} = 0.902$, $p = 0.355$,
407 $BF_{10} = 0.078$), and implicit wanting ($F_{(1, 17)} = 0.786$, $p = 0.388$, $BF_{10} = 0.076$). Again, this is
408 supported by strong evidence in favour of the null hypothesis over the alternative hypothesis
409 and the effects remained non-significant when controlling for baseline hunger (p 's > 0.40)
410 and behaviour trait scores (p 's > 0.42). Similar non-significant condition * time point
411 interactions were seen for FAB explicit wanting ($F_{(1, 18)} = 0.136$, $p = 0.716$, $BF_{10} = 0.183$) and
412 implicit wanting ($F_{(1, 17)} = 0.646$, $p = 0.433$, $BF_{10} = 0.111$). These scores remained non-
413 significant when controlling for baseline hunger ($p = 0.823$ and 0.236 , respectively) and
414 behaviour trait scores (p 's > 0.24). However, there was a significant time point ($F_{(1, 18)} =$
415 6.785 , $p = 0.018$) and condition * time point interaction for FAB explicit liking ($F_{(1, 18)} = 7.374$,
416 $p = 0.014$, $BF_{10} = 0.545$); scores increased following both active and sham tDCS, and to a
417 greater extent following active stimulation (Table 3). After controlling for baseline hunger
418 scores this effect was no longer significant ($F_{(1, 36)} = 2.944$, $p = 0.095$, $BF_{10} = 0.313$).
419 Similarly, when controlling for baseline behaviour trait scores no significant effects were
420 identified (p 's > 0.08).

421

422 **Table 3** Pre-stimulation and post-stimulation LFPQ scores ($n = 21$).

		Explicit Liking (mm)		Explicit Wanting (mm)		Implicit Wanting (AU)	
		Pre-tDCS	Post-tDCS	Pre-tDCS	Post-tDCS	Pre-tDCS	Post-tDCS
Active	HFSA	52.9 ± 23.9	64.7 ± 25.1	49.9 ± 23.8	59.9 ± 25.7	-0.7 ± 31.0	15.7 ± 47.7
	LFSA	54.0 ± 20.9	53.7 ± 22.0	53.3 ± 22.1	53.6 ± 19.3	-1.4 ± 24.9	-15.1 ± 38.7
	HFSW	48.2 ± 24.6	54.6 ± 23.0	48.0 ± 24.2	48.8 ± 24.4	-6.5 ± 27.9	-3.6 ± 26.6
	LFSW	60.2 ± 20.8	60.5 ± 21.8	60.0 ± 19.5	57.1 ± 19.5	10.8 ± 28.7	3.8 ± 26.5
	FAB	-6.6 ± 24.1*	2.5 ± 21.4*	-7.8 ± 25.0	-1.0 ± 23.3	-7.1 ± 45.3	12.1 ± 53.7
	TAB	0.7 ± 18.2	-1.6 ± 20.0	2.4 ± 15.5	-3.9 ± 19.3	3.8 ± 20.2	-9.5 ± 39.1
Sham	HFSA	53.8 ± 26.6	57.2 ± 25.2	51.8 ± 27.7	55.1 ± 25.8	9.6 ± 33.1	14.4 ± 28.5
	LFSA	49.7 ± 18.4	49.8 ± 18.1	49.7 ± 20.1	49.8 ± 18.2	-2.3 ± 25.2	-3.6 ± 23.5
	HFSW	49.0 ± 27.6	47.1 ± 26.4	42.6 ± 28.0	45.9 ± 26.1	-9.5 ± 29.5	-6.9 ± 30.9
	LFSW	57.4 ± 22.3	55.4 ± 19.0	56.8 ± 20.1	53.5 ± 20.5	5.5 ± 30.0	-0.6 ± 29.4
	FAB	-2.1 ± 26.3*	-0.4 ± 23.2*	-6.1 ± 29.6	-1.1 ± 23.8	0.2 ± 45.0	7.6 ± 41.9
	TAB	1.4 ± 18.9	-2.3 ± 12.9	-1.0 ± 16.3	-2.8 ± 11.6	-5.3 ± 29.4	-8.7 ± 25.6

Mean ± SD. HFSA, high-fat savoury; LFSA, low-fat savoury; HFSW, high-fat sweet; LFSW, low-fat sweet; FAB, fat appeal bias; TAB, taste appeal bias. * Indicates significant difference between active and sham conditions ($p < 0.05$).

424

425 **3.4 Test-Retest Analysis**

426 With the exception of desire to eat ($r = 0.382$, $p = 0.088$), all variables were significantly
427 correlated between baseline assessment. Twelve of the 23 variables assessed (across
428 measurement instruments) displayed a strong correlation ($r = >0.7$), with LFPQ implicit
429 wanting and FAB appearing most consistent. Some baseline measures, particularly FCQ-S
430 and appetite VAS measures, indicated only moderate reliability ($r = 0.5$ to 0.7 ; Table 4).

431

432 **Table 4** Correlations between baseline (pre-tDCS) measures during visits 2 and 3 ($n = 21$).

			<i>r</i>	<i>p</i>
Food Craving Questionnaire-State			0.549	0.010
Appetite VAS	Hunger		0.654	0.001
	Fullness		0.588	0.005
	Prospective Consumption		0.841	<0.001
	Desire to Eat		0.382	0.088
LFPQ	Implicit Wanting	HFSA	0.837	<0.001
		LFSA	0.795	<0.001
		HFSW	0.882	<0.001
		LFSW	0.718	0.001
	Explicit Liking	HFSA	0.652	0.002
		LFSA	0.664	0.002
		HFSW	0.781	<0.001
		LFSW	0.784	<0.001
	Explicit Wanting	HFSA	0.698	0.001
		LFSA	0.751	<0.001
		HFSW	0.712	0.001
		LFSW	0.668	0.002
	Fat Appeal Bias	Explicit Liking	0.853	<0.001
		Explicit Wanting	0.887	<0.001
		Implicit Wanting	0.677	0.001
	Taste Appeal Bias	Explicit Liking	0.536	0.018
Explicit Wanting		0.555	0.014	
Implicit Wanting		0.737	<0.001	

HFSA, high-fat savoury; HFSW, high-fat sweet; LFPQ, Leeds Food Preference

Questionnaire; LFSA, low-fat savoury; LFSW, low-fat sweet; VAS, visual analogue scale.

433

434 **3.5 Responses to tDCS**

435 Successful delivery of the electric current occurred across all 42 stimulation sessions, with
436 mean impedance levels of 8 ± 4 k Ω at the start of stimulation which reduced to 3 ± 2 k Ω
437 within the initial five minutes of current delivery. Stimulation was well-tolerated by
438 participants with only common adverse events, particularly cutaneous sensations,
439 experienced during tDCS. The most common sensations reported were tingling, itching,
440 sleepiness and a burning sensation (Table 5). Tingling ($p = 0.016$), itching ($p = 0.021$) and
441 sleepiness ($p = 0.021$) were reported by significantly more participants following active
442 tDCS, when compared with sham stimulation. No other sensations were significantly
443 different between conditions. Despite experiencing more minor adverse events, participants
444 were unable to identify the active tDCS session above the level of chance, with only 38%
445 (8/21) of participants able to successfully distinguish between conditions.

446

447 **Table 5** Frequency of adverse events experienced immediately post-stimulation.

	Active	Sham	p
Headache	7 (33%)	4 (19%)	0.186
Neck pain	0 (0%)	0 (0%)	-
Scalp pain	3 (14%)	1 (5%)	0.329
Tingling	14 (67%)	7 (33%)	0.016*
Itching	11 (52%)	6 (29%)	0.021*
Burning sensation	9 (43%)	2 (10%)	0.267
Skin redness	5 (24%)	2 (10%)	0.186
Sleepiness	12 (57%)	7 (33%)	0.021*
Trouble concentrating	5 (24%)	3 (14%)	0.329
Acute mood change	2 (10%)	2 (10%)	1.000

* Indicates significant difference between active and sham conditions.

448

449 **4. DISCUSSION**

450 The current study examined the effect of induced hyper-activity of the right DLPFC through
 451 tDCS on food craving, reward and subjective appetite measures in a healthy-weight cohort.

452 It is important to note that the sample used in the current study appeared to show low
 453 susceptibility to hedonic-driven overconsumption, evidenced by their scores on several
 454 measures of eating behaviour traits linked to overconsumption. We also sought to examine
 455 the reliability of measures prior to tDCS with a view to establishing the viability of their future
 456 use in our research. We report strong relationships between key variables, particularly
 457 implicit wanting and FAB, when preparatory procedures prior to tDCS were standardised.

458 These variables may prove to be sensitive targets for detecting significant effects in future
 459 eating behaviour-focussed tDCS research. Other variables, particularly food craving
 460 measures, proved less stable and may require tighter experimental control or larger sample
 461 sizes to reveal differences. Collectively our findings are novel to tDCS research.

462

463 Prior work has mainly focussed on measuring food craving and in-laboratory consumption
464 with equivocal findings (Fregni, et al., 2008; Georgii, et al., 2017; Goldman, et al., 2011;
465 Sedgmond, et al., 2019). The present study is favourable by comparison in sample size,
466 study design (i.e. sham-controlled and double-blind) and stimulation parameters (Burgess, et
467 al., 2016; Fregni, et al., 2008; Goldman, et al., 2011; Ray, et al., 2017). Recently published
468 meta-analyses have cast doubt in the ability of tDCS to alter measures of food craving (Hall
469 & Lowe, 2018; Lowe, Vincent, & Hall, 2017), which may be due to the poor test-retest
470 reliability of food craving measures (Cepeda-Benito, et al., 2000; Meule, Teran, et al., 2014).
471 This is in agreement with our data which highlighted only moderate reliability of baseline
472 FCQ-S scores. In comparison, our data show strong relationships between baseline
473 measures of implicit and explicit reward. In developing the LFPQ, Dalton and Finlayson
474 (2014) reported a reliability coefficient of 0.6 – 0.7 for implicit wanting and 0.8 – 0.9 for
475 explicit liking measures, with our data supporting this moderate-to-strong reliability. The
476 LFPQ has been utilised in several settings, and is considered a sensitive measure for
477 individual eating behaviour traits (Dalton, et al., 2013a; Dalton, Blundell, & Finlayson, 2013b;
478 Finlayson, Arlotti, Dalton, King, & Blundell, 2011), and a good predictor of in-laboratory and
479 real-world food choice and consumption (French, Mitchell, Finlayson, Blundell, & Jeffery,
480 2014; Griffioen-Roose, Mars, Finlayson, Blundell, & de Graaf, 2011). The present study is
481 the first to extend the use of the LFPQ to include tDCS procedures, and the reliability of this
482 questionnaire suggests it is a robust measure and should be explored in future research.

483

484 It is logical that the significant interaction between tDCS condition and time point for FAB
485 explicit liking was removed when controlling for baseline hunger as the excitatory effects of
486 anodal tDCS are not associated with increased preference for high-fat foods (Goldman, et
487 al., 2011; Jauch-Chara, et al., 2014). In addition, healthy individuals are likely to have a
488 normative response to food stimuli and are able to sufficiently integrate rewarding signals
489 with other appetitive signals to select appropriate eating behaviours (see Alonso-Alonso and

490 Pascual-Leone (2007) for review). Healthy individuals are also unlikely to have structural
491 deficits observed in obesity and binge eating, which are associated with alteration in reward
492 response (Balodis, Grilo, & Potenza, 2015; Lowe, Reichelt, & Hall, 2019). It is probable that
493 stimulation would have no additive effects in healthy individuals (Burgess, et al., 2016). The
494 greater baseline hunger score likely heightened the rewarding value of high-calorie foods,
495 particularly those high in fat, that participants were exposed to during the computer-based
496 task (Cameron, Goldfield, Finlayson, Blundell, & Doucet, 2014; Finlayson, King, & Blundell,
497 2008; Mehta, et al., 2012).

498

499 In addition to the equivocal findings for food craving and consumption, previous work has
500 been inconsistent in the recruitment of participants and some of the variation in results may
501 be due to participants' eating behaviour traits. Two previous studies have directly linked
502 tDCS effects as occurring in those with abnormal eating behaviours (Burgess, et al., 2016;
503 Ray, et al., 2017), and when comparing further studies that utilise similar tDCS parameters
504 (i.e. 2 mA for 20 minutes over the right DLPFC), a trait-dependent effect is evident. Studies
505 that recruited participants with frequent food cravings found a consistent reduction in
506 measures of state food craving (Fregni, et al., 2008; Goldman, et al., 2011; Kekic, et al.,
507 2014; Lapenta, et al., 2014). In comparison, studies that did not measure behaviour traits or
508 report comparable traits between healthy and overweight populations, fail to find a significant
509 effect of stimulation on craving (Bravo, et al., 2016; Sedgmond, et al., 2019). Our data
510 supports the robustness of healthy eating behaviours against perturbation in cortical activity
511 within the DLPFC, which is assumed to occur in populations that are obese or with BED
512 (Boeka & Lokken, 2011; Karhunen, et al., 2000). We therefore speculate that there is a
513 diminishing return for attempting to increase neuronal activity within the DLPFC when
514 participants are already able to control their eating behaviours. Hyper-activity in this cortical
515 region may have a ceiling effect beyond which no further improvement is seen. This may
516 account for the null effect we found for food craving, reward and appetite following tDCS,

517 and can be supported by the moderate-to-strong evidence in favour of the null hypothesis as
518 highlighted by our Bayesian statistical approach.

519

520 The present study is not without limitation. It is understood that males and females
521 experience different eating behaviours, and may express differing behavioural traits (Rolls,
522 Fedoroff, & Guthrie, 1991). The present study recruited both male and female participants,
523 which may have influenced the effects of tDCS, and provided an additional source of
524 variation across data. However, this is not without precedent as prior studies that recruited
525 male and female participants have shown an experimental effect (Burgess, et al., 2016;
526 Carvalho, et al., 2019; Goldman, et al., 2011). Given the novelty of using the LFPQ it was
527 important to consider the wider effects of tDCS on this variable before focussing on specific
528 sex. Second, our original hypotheses did not consider the impact of eating behaviour traits
529 and as such these were not controlled for during screening. Our inclusion criteria focussed
530 on weight status, but the participants recruited displayed behaviour traits that do not suggest
531 susceptibility to overconsumption, as discussed above; notably, all participants scored below
532 the 50-point cut-off for trait food craving. Third, prior studies have induced hyperactivity in
533 the DLPFC through bilateral and unilateral stimulation of the cortex (Carvalho, et al., 2019;
534 Fassini, et al., 2019; Lapenta, et al., 2014; Ljubisavljevic, et al., 2016). Although these
535 montages have been shown to improve measures of hedonic appetite (Fregni, et al., 2008;
536 Goldman, et al., 2011), the efficacy of such electrode placement has been debated due to
537 the simultaneous effects of anodal and cathodal stimulation on the same cortical region
538 (Bestmann, et al., 2015). The inhibitory effects associated with cathodal stimulation during
539 traditional montages may also impact hedonic appetite measures, as the left DLPFC is
540 implicated in dietary control and food choice behaviour (Higuera-Hernández, et al., 2018).
541 Similar to the right DLPFC, there is some support for reduced activity in the left DLPFC in
542 response to food, when comparing individuals who are lean with those who are obese (Le, et
543 al., 2006; Le, et al., 2007). In the present study, a prefrontal-occipital montage was used,
544 utilising a similar montage seen in previous work (Marron, et al., 2018; Vitor-Costa, et al.,

545 2015). The ability of this montage to induce hyperactivity in the DLPFC has been confirmed
546 in several recent computational models (Marron, et al., 2018; Zheng, et al., 2016; Zheng, et
547 al., 2017). Moreover, we verified that the electric current was being delivered in a consistent
548 manner across all 42 stimulation sessions by checking impedance. Finally, the effectiveness
549 of common sham procedures as a blinding technique has been debated due to significantly
550 greater sensations often reported following active tDCS (Horvath, 2015). Indeed, in the
551 present study participants reported significantly greater itching, tingling and sleepiness
552 following active stimulation. However, the inability of participants to identify the active
553 protocol beyond the level of chance, despite these heightened sensations, provides further
554 support for the use of standardised sham protocols as a blinding technique in tDCS research
555 (Ambrus, et al., 2012).

556

557 **5. CONCLUSION**

558 Our study is the first to report the effects of tDCS on components of food reward in sample of
559 healthy individuals with no susceptibility to overconsume, and we show no significant change
560 in these measures. Prior to examining these effects, we established an indication of data
561 reliability and revealed some plausible targets for future effects through tDCS exposure. In
562 the present sample these effects were transient for the most part and, in line with the work
563 by Burgess and colleagues (Burgess, et al., 2016; Ray, et al., 2017), this highlights a
564 behaviour trait-dependent effect of stimulation. Future work should focus on populations who
565 are at risk of reward-driven overconsumption and weight gain, such as those showing
566 recurrent binge eating behaviours, as these individuals may be responsive to the effects of
567 tDCS on hedonic appetite.

568

569 **ACKNOWLEDGEMENTS**

570 The authors wish to thank Elizabeth Senior and Lee Newburn for their help with recruitment
571 and data collection, and Dr Jo Corbett of the University of Portsmouth for advising on
572 protocol development.

573

574 **AUTHOR CONTRIBUTIONS**

575 **Jordan Beaumont:** Conceptualisation, Methodology, Validation, Formal analysis,

576 Investigation, Data curation, Writing – original draft, Writing – review and editing,

577 Visualisation, Project administration.

578 **Danielle Davis:** Conceptualisation, Methodology, Resources, Writing – review and editing,

579 Supervision.

580 **Michelle Dalton:** Conceptualisation, Methodology, Software, Formal analysis, Resources,

581 Data curation, Writing – review and editing.

582 **Alexander Nowicky:** Methodology, Writing – review and editing.

583 **Mark Russell:** Methodology, Writing – review and editing.

584 **Martin Barwood:** Conceptualisation, Methodology, Validation, Resources, Writing – original

585 draft, Writing – review and editing, Supervision.

586

587 **DECLARATION OF INTEREST**

588 None.

589

590 **FUNDING**

591 This research did not receive any specific grant from funding agencies in the public,

592 commercial or not-for-profit sectors.

593

594 **REFERENCES**

- 595 Alonso-Alonso, M. (2013). Translating tDCS into the field of obesity: mechanism-driven
596 approaches. *Frontiers in Human Neuroscience*, 7, 512.
- 597 Alonso-Alonso, M., & Pascual-Leone, A. (2007). The Right Brain Hypothesis for Obesity.
598 *JAMA*, 297, 1819-1822.
- 599 Alonzo, A., Brassil, J., Taylor, J. L., Martin, D., & Loo, C. K. (2012). Daily transcranial direct
600 current stimulation (tDCS) leads to greater increases in cortical excitability than
601 second daily transcranial direct current stimulation. *Brain Stimulation*, 5, 208-213.
- 602 Ambrus, G. G., Al-Moyed, H., Chaieb, L., Sarp, L., Antal, A., & Paulus, W. (2012). The fade-
603 in – Short stimulation – Fade out approach to sham tDCS – Reliable at 1 mA for
604 naïve and experienced subjects, but not investigators. *Brain Stimulation*, 5, 499-504.
- 605 Andresen, E. M., Malmgren, J. A., Carter, W. B., & Patrick, D. L. (1994). Screening for
606 depression in well older adults: Evaluation of a short form of the CES-D. *American*
607 *Journal of Preventive Medicine*, 10, 77-84.
- 608 Anglé, S., Engblom, J., Eriksson, T., Kautiainen, S., Saha, M.-T., Lindfors, P., Lehtinen, M.,
609 & Rimpelä, A. (2009). Three factor eating questionnaire-R18 as a measure of
610 cognitive restraint, uncontrolled eating and emotional eating in a sample of young
611 Finnish females. *International Journal of Behavioral Nutrition and Physical Activity*, 6,
612 41.
- 613 Balodis, I. M., Grilo, C. M., & Potenza, M. N. (2015). Neurobiological features of binge eating
614 disorder. *CNS spectrums*, 20, 557-565.
- 615 Beechy, L., Galpern, J., Petrone, A., & Das, S. K. (2012). Assessment tools in obesity —
616 Psychological measures, diet, activity, and body composition. *Physiology & Behavior*,
617 107, 154-171.
- 618 Bestmann, S., de Berker, A. O., & Bonaiuto, J. (2015). Understanding the behavioural
619 consequences of noninvasive brain stimulation. *Trends in Cognitive Sciences*, 19,
620 13-20.
- 621 Blundell, J., De Graaf, C., Hulshof, T., Jebb, S., Livingstone, B., Lluch, A., Mela, D., Salah,
622 S., Schuring, E., Van Der Knaap, H., & Westerterp, M. (2010). Appetite control:
623 methodological aspects of the evaluation of foods. *Obesity Reviews*, 11, 251-270.
- 624 Boeka, A. G., & Lokken, K. L. (2011). Prefrontal systems involvement in binge eating. *Eating*
625 *and Weight Disorders - Studies on Anorexia, Bulimia and Obesity*, 16, e121-e126.
- 626 Boswell, R. G., & Kober, H. (2016). Food cue reactivity and craving predict eating and weight
627 gain: a meta-analytic review. *Obesity Reviews*, 17, 159-177.
- 628 Bravo, G. L., Poje, A. B., Perissinotti, I., Marcondes, B. F., Villamar, M. F., Manzardo, A. M.,
629 Luque, L., LePage, J. F., Stafford, D., Fregni, F., & Butler, M. G. (2016). Transcranial
630 direct current stimulation reduces food-craving and measures of hyperphagia

- 631 behavior in participants with Prader-Willi syndrome. *American Journal of Medical*
632 *Genetics Part B: Neuropsychiatric Genetics*, 171, 266-275.
- 633 Brunoni, A. R., Amadera, J., Berbel, B., Volz, M. S., Rizzerio, B. G., & Fregni, F. (2011). A
634 systematic review on reporting and assessment of adverse effects associated with
635 transcranial direct current stimulation. *International Journal of*
636 *Neuropsychopharmacology*, 14, 1133-1145.
- 637 Burgess, E. E., Sylvester, M. D., Morse, K. E., Amthor, F. R., Mrug, S., Lokken, K. L.,
638 Osborn, M. K., Soleymani, T., & Boggiano, M. M. (2016). Effects of transcranial direct
639 current stimulation (tDCS) on binge-eating disorder. *International Journal of Eating*
640 *Disorders*, 49, 930-936.
- 641 Cameron, J. D., Goldfield, G. S., Finlayson, G., Blundell, J. E., & Doucet, É. (2014). Fasting
642 for 24 Hours Heightens Reward from Food and Food-Related Cues. *PLOS ONE*, 9,
643 e85970.
- 644 Carvalho, S., Sampaio, A., Mendes, A. J., Lema, A., Vieira, D., Gonçalves, Ó. F., & Leite, J.
645 (2019). Polarity Specific Effects of Cross-Hemispheric tDCS Coupled With Approach-
646 Avoidance Training on Chocolate Craving. *Frontiers in Pharmacology*, 9, 1500.
- 647 Cepeda-Benito, A., Gleaves, D. H., Williams, T. L., & Erath, S. A. (2000). The development
648 and validation of the state and trait food-cravings questionnaires. *Behavior Therapy*,
649 31, 151-173.
- 650 Dalton, M., Blundell, J., & Finlayson, G. (2013a). Effect of BMI and Binge Eating on Food
651 Reward and Energy Intake: Further Evidence for a Binge Eating Subtype of Obesity.
652 *Obesity Facts*, 6, 348-359.
- 653 Dalton, M., Blundell, J., & Finlayson, G. (2013b). Examination of food reward and energy
654 intake under laboratory and free-living conditions in a trait binge eating subtype of
655 obesity. *Frontiers in Psychology*, 4, 757.
- 656 Dalton, M., & Finlayson, G. (2014). Psychobiological examination of liking and wanting for fat
657 and sweet taste in trait binge eating females. *Physiology & Behavior*, 136, 128-134.
- 658 Dalton, M., Finlayson, G., Hill, A., & Blundell, J. (2015). Preliminary validation and principal
659 components analysis of the Control of Eating Questionnaire (CoEQ) for the
660 experience of food craving. *European Journal Of Clinical Nutrition*, 69, 1313.
- 661 Dalton, M., Finlayson, G., Walsh, B., Halseth, A. E., Duarte, C., & Blundell, J. E. (2017).
662 Early improvement in food cravings are associated with long-term weight loss
663 success in a large clinical sample. *International Journal Of Obesity*, 41, 1232-1236.
- 664 DaSilva, A. F., Volz, M. S., Bikson, M., & Fregni, F. (2011). *Electrode Positioning and*
665 *Montage in Transcranial Direct Current Stimulation*.
666 <[https://www.jove.com/video/2744/electrode-positioning-montage-transcranial-direct-](https://www.jove.com/video/2744/electrode-positioning-montage-transcranial-direct-current)
667 [current](https://www.jove.com/video/2744/electrode-positioning-montage-transcranial-direct-current)> Accessed 09 June 2020.

- 668 Davis, C. (2013). Compulsive Overeating as an Addictive Behavior: Overlap Between Food
669 Addiction and Binge Eating Disorder. *Current Obesity Reports*, 2, 171-178.
- 670 Davis, C., Levitan, R. D., Reid, C., Carter, J. C., Kaplan, A. S., Patte, K. A., King, N., Curtis,
671 C., & Kennedy, J. L. (2009). Dopamine for “Wanting” and Opioids for “Liking”: A
672 Comparison of Obese Adults With and Without Binge Eating. *Obesity*, 17, 1220-
673 1225.
- 674 De Lauzon-Guillain, B., Romon, M., Musher-Eizenman, D., Heude, B., Basdevant, A.,
675 Charles, M. A., & Fleurbaix-Laventie Ville Santé Study, G. (2009). Cognitive restraint,
676 uncontrolled eating and emotional eating: correlations between parent and
677 adolescent. *Maternal & Child Nutrition*, 5, 171-178.
- 678 Fassini, P. G., Das, S. K., Suen, V. M. M., Magerowski, G., Marchini, J. S., da Silva Junior,
679 W. A., Changyu, S., & Alonso-Alonso, M. (2019). Appetite effects of prefrontal
680 stimulation depend on COMT Val158Met polymorphism: A randomized clinical trial.
681 *Appetite*, 140, 142-150.
- 682 Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical
683 power analysis program for the social, behavioral, and biomedical sciences. *Behavior*
684 *Research Methods*, 39, 175-191.
- 685 Filmer, H. L., Dux, P. E., & Mattingley, J. B. (2014). Applications of transcranial direct current
686 stimulation for understanding brain function. *Trends in Neurosciences*, 37, 742-753.
- 687 Finlayson, G., Arlotti, A., Dalton, M., King, N., & Blundell, J. E. (2011). Implicit wanting and
688 explicit liking are markers for trait binge eating. A susceptible phenotype for
689 overeating. *Appetite*, 57, 722-728.
- 690 Finlayson, G., & Dalton, M. (2012). Hedonics of Food Consumption: Are Food ‘Liking’ and
691 ‘Wanting’ Viable Targets for Appetite Control in the Obese? *Current Obesity Reports*,
692 1, 42-49.
- 693 Finlayson, G., King, N., & Blundell, J. (2008). The role of implicit wanting in relation to explicit
694 liking and wanting for food: Implications for appetite control. *Appetite*, 50, 120-127.
- 695 Finlayson, G., King, N., & Blundell, J. E. (2007). Is it possible to dissociate ‘liking’ and
696 ‘wanting’ for foods in humans? A novel experimental procedure. *Physiology &*
697 *Behavior*, 90, 36-42.
- 698 Fleurbaix Laventie Ville Sante Study, G. (2004). The Three-Factor Eating Questionnaire-R18
699 Is Able to Distinguish among Different Eating Patterns in a General Population. *The*
700 *Journal of Nutrition*, 134, 2372-2380.
- 701 Fregni, F., Orsati, F., Pedrosa, W., Fecteau, S., Tome, F. A., Nitsche, M. A., Mecca, T.,
702 Macedo, E. C., Pascual-Leone, A., & Boggio, P. S. (2008). Transcranial direct current
703 stimulation of the prefrontal cortex modulates the desire for specific foods. *Appetite*,
704 51, 34-41.

- 705 French, S. A., Mitchell, N. R., Finlayson, G., Blundell, J. E., & Jeffery, R. W. (2014).
706 Questionnaire and laboratory measures of eating behavior. Associations with energy
707 intake and BMI in a community sample of working adults. *Appetite*, *72*, 50-58.
- 708 Galetta, S. L. (2017). Occipital Lobe☆. In *Reference Module in Neuroscience and*
709 *Biobehavioral Psychology*. Elsevier.
- 710 Gandiga, P. C., Hummel, F. C., & Cohen, L. G. (2006). Transcranial DC stimulation (tDCS):
711 A tool for double-blind sham-controlled clinical studies in brain stimulation. *Clinical*
712 *Neurophysiology*, *117*, 845-850.
- 713 Georgii, C., Goldhofer, P., Meule, A., Richard, A., & Blechert, J. (2017). Food craving, food
714 choice and consumption: The role of impulsivity and sham-controlled tDCS
715 stimulation of the right dlPFC. *Physiology & Behavior*, *177*, 20-26.
- 716 Gluck, M. E., Alonso-Alonso, M., Piaggi, P., Weise, C. M., Jumpertz-von Schwartzberg,
717 R., Reinhardt, M., Wassermann, E. M., Venti, C. A., Votruba, S. B., & Krakoff, J.
718 (2015). Neuromodulation targeted to the prefrontal cortex induces changes in energy
719 intake and weight loss in obesity. *Obesity (Silver Spring)*, *23*, 2149-2156.
- 720 Gluck, M. E., Viswanath, P., & Stinson, E. J. (2017). Obesity, Appetite, and the Prefrontal
721 Cortex. *Curr Obes Rep*, *6*, 380-388.
- 722 Goldman, R. L., Borckardt, J. J., Frohman, H. A., O'Neil, P. M., Madan, A., Campbell, L. K.,
723 Budak, A., & George, M. S. (2011). Prefrontal cortex transcranial direct current
724 stimulation (tDCS) temporarily reduces food cravings and increases the self-reported
725 ability to resist food in adults with frequent food craving. *Appetite*, *56*, 741-746.
- 726 Griffioen-Roose, S., Mars, M., Finlayson, G., Blundell, J. E., & de Graaf, C. (2011). The
727 effect of within-meal protein content and taste on subsequent food choice and
728 satiety. *British Journal of Nutrition*, *106*, 779-788.
- 729 Hall, P. A., & Lowe, C. J. (2018). Cravings, currents and cadavers: What is the magnitude of
730 tDCS effects on food craving outcomes? *Nutritional Neuroscience*, 1-4.
- 731 Hall, P. A., Vincent, C. M., & Burhan, A. M. (2018). Non-invasive brain stimulation for food
732 cravings, consumption, and disorders of eating: A review of methods, findings and
733 controversies. *Appetite*, *124*, 78-88.
- 734 Higuera-Hernández, M. F., Reyes-Cuapio, E., Gutiérrez-Mendoza, M., Rocha, N. B., Veras,
735 A. B., Budde, H., Jesse, J., Zaldívar-Rae, J., Blanco-Centurión, C., Machado, S., &
736 Murillo-Rodríguez, E. (2018). Fighting obesity: Non-pharmacological interventions.
737 *Clinical Nutrition ESPEN*, *25*, 50-55.
- 738 Hill, J. O. (2006). Understanding and Addressing the Epidemic of Obesity: An Energy
739 Balance Perspective. *Endocrine Reviews*, *27*, 750-761.
- 740 Horvath, J. C. (2015). Are current blinding methods for transcranial direct current stimulation
741 (tDCS) effective in healthy populations? *Clinical Neurophysiology*, *126*, 2045-2046.

- 742 Jamil, A., & Nitsche, M. A. (2017). What Effect Does tDCS Have on the Brain? Basic
743 Physiology of tDCS. *Current Behavioral Neuroscience Reports*, 4, 331-340.
- 744 Jauch-Chara, K., Kistenmacher, A., Herzog, N., Schwarz, M., Schweiger, U., & Oltmanns, K.
745 M. (2014). Repetitive electric brain stimulation reduces food intake in humans. *The*
746 *American Journal of Clinical Nutrition*, 100, 1003-1009.
- 747 Joseph, R. J., Alonso-Alonso, M., Bond, D. S., Pascual-Leone, A., & Blackburn, G. L. (2011).
748 The neurocognitive connection between physical activity and eating behaviour.
749 *Obesity Reviews*, 12, 800-812.
- 750 Karhunen, L. J., Vanninen, E. J., Kuikka, J. T., Lappalainen, R. I., Tiihonen, J., & Uusitupa,
751 M. I. J. (2000). Regional cerebral blood flow during exposure to food in obese binge
752 eating women. *Psychiatry Research: Neuroimaging*, 99, 29-42.
- 753 Karlsson, J., Persson, L. O., Sjöström, L., & Sullivan, M. (2000). Psychometric properties
754 and factor structure of the Three-Factor Eating Questionnaire (TFEQ) in obese men
755 and women. Results from the Swedish Obese Subjects (SOS) study. *International*
756 *Journal Of Obesity*, 24, 1715-1725.
- 757 Kekic, M., McClelland, J., Campbell, I., Nestler, S., Rubia, K., David, A. S., & Schmidt, U.
758 (2014). The effects of prefrontal cortex transcranial direct current stimulation (tDCS)
759 on food craving and temporal discounting in women with frequent food cravings.
760 *Appetite*, 78, 55-62.
- 761 Kessler, R. C., Berglund, P. A., Chiu, W. T., Deitz, A. C., Hudson, J. I., Shahly, V., Aguilar-
762 Gaxiola, S., Alonso, J., Angermeyer, M. C., Benjet, C., Bruffaerts, R., de Girolamo,
763 G., de Graaf, R., Maria Haro, J., Kovess-Masfety, V., O'Neill, S., Posada-Villa, J.,
764 Sasu, C., Scott, K., Viana, M. C., & Xavier, M. (2013). The Prevalence and
765 Correlates of Binge Eating Disorder in the World Health Organization World Mental
766 Health Surveys. *Biological Psychiatry*, 73, 904-914.
- 767 Klem, G. H., Lüders, H. O., Jasper, H. H., & Elger, C. (1999). The ten-twenty electrode
768 system of the International Federation. The International Federation of Clinical
769 Neurophysiology. *Electroencephalography and clinical neurophysiology. Supplement*,
770 52, 3-6.
- 771 Kober, H., & Boswell, R. G. (2018). Potential psychological & neural mechanisms in binge
772 eating disorder: Implications for treatment. *Clinical Psychology Review*, 60, 32-44.
- 773 Lapenta, O. M., Sierve, K. D., de Macedo, E. C., Fregni, F., & Boggio, P. S. (2014).
774 Transcranial direct current stimulation modulates ERP-indexed inhibitory control and
775 reduces food consumption. *Appetite*, 83, 42-48.
- 776 Le, D. S. N. T., Pannacciulli, N., Chen, K., Del Parigi, A., Salbe, A. D., Reiman, E. M., &
777 Krakoff, J. (2006). Less activation of the left dorsolateral prefrontal cortex in response
778 to a meal: a feature of obesity. *The American Journal of Clinical Nutrition*, 84, 725-
779 731.

- 780 Le, D. S. N. T., Pannacciulli, N., Chen, K., Salbe, A. D., Hill, J. O., Wing, R. R., Reiman, E.
781 M., & Krakoff, J. (2007). Less activation in the left dorsolateral prefrontal cortex in the
782 reanalysis of the response to a meal in obese than in lean women and its association
783 with successful weight loss. *The American Journal of Clinical Nutrition*, 86, 573-579.
- 784 Lee, M., & Wagenmakers, E. (2013). *Bayesian Cognitive Modeling: A Practical Course*.
785 United Kingdom: Cambridge University Press.
- 786 Ljubisavljevic, M., Maxood, K., Bjekic, J., Oommen, J., & Nagelkerke, N. (2016). Long-Term
787 Effects of Repeated Prefrontal Cortex Transcranial Direct Current Stimulation (tDCS)
788 on Food Craving in Normal and Overweight Young Adults. *Brain Stimulation*, 9, 826-
789 833.
- 790 Lowe, C. J., Reichelt, A. C., & Hall, P. A. (2019). The Prefrontal Cortex and Obesity: A
791 Health Neuroscience Perspective. *Trends in Cognitive Sciences*, 23, 349-361.
- 792 Lowe, C. J., Vincent, C., & Hall, P. A. (2017). Effects of Noninvasive Brain Stimulation on
793 Food Cravings and Consumption: A Meta-Analytic Review. *Psychosomatic Medicine*,
794 79.
- 795 Marron, E. M., Viejo-Sobera, R., Cuatrecasas, G., Redolar-Ripoll, D., Lorda, P. G., Datta, A.,
796 Bikson, M., Magerowski, G., & Alonso-Alonso, M. (2018). Prefronto-cerebellar
797 neuromodulation affects appetite in obesity. *International Journal Of Obesity*.
- 798 Mehta, S., Melhorn, S. J., Smeraglio, A., Tyagi, V., Grabowski, T., Schwartz, M. W., & Schur,
799 E. A. (2012). Regional brain response to visual food cues is a marker of satiety that
800 predicts food choice. *The American Journal of Clinical Nutrition*, 96, 989-999.
- 801 Meule, A. (2018). Food cravings in food addiction: exploring a potential cut-off value of the
802 Food Cravings Questionnaire-Trait-reduced. *Eating and Weight Disorders - Studies*
803 *on Anorexia, Bulimia and Obesity*, 23, 39-43.
- 804 Meule, A., Hermann, T., & Kübler, A. (2014). A short version of the Food Cravings
805 Questionnaire—Trait: the FCQ-T-reduced. *Frontiers in Psychology*, 5, 190.
- 806 Meule, A., Teran, C. B., Berker, J., Gründel, T., Mayerhofer, M., & Platte, P. (2014). On the
807 differentiation between trait and state food craving: Half-year retest-reliability of the
808 Food Cravings Questionnaire-Trait-reduced (FCQ-T-r) and the Food Cravings
809 Questionnaire-State(FCQ-S). *Journal of Eating Disorders*, 2, 25.
- 810 Nikolin, S., Huggins, C., Martin, D., Alonzo, A., & Loo, C. K. (2018). Safety of repeated
811 sessions of transcranial direct current stimulation: A systematic review. *Brain*
812 *Stimulation*, 11, 278-288.
- 813 Nitsche, M. A., & Paulus, W. (2000). Excitability changes induced in the human motor cortex
814 by weak transcranial direct current stimulation. *The Journal of Physiology*, 527, 633-
815 639.
- 816 Nitsche, M. A., & Paulus, W. (2001). Sustained excitability elevations induced by transcranial
817 DC motor cortex stimulation in humans. *Neurology*, 57, 1899.

- 818 Oustric, P., Thivel, D., Dalton, M., Beaulieu, K., Gibbons, C., Hopkins, M., Blundell, J., &
819 Finlayson, G. (2020). Measuring food preference and reward: Application and cross-
820 cultural adaptation of the Leeds Food Preference Questionnaire in human
821 experimental research. *Food Quality and Preference*, *80*, 103824.
- 822 Radloff, L. S. (1977). The CES-D Scale: A Self-Report Depression Scale for Research in the
823 General Population. *Applied Psychological Measurement*, *1*, 385-401.
- 824 Ray, M. K., Sylvester, M. D., Osborn, L., Helms, J., Turan, B., Burgess, E. E., & Boggiano,
825 M. M. (2017). The critical role of cognitive-based trait differences in transcranial direct
826 current stimulation (tDCS) suppression of food craving and eating in frank obesity.
827 *Appetite*, *116*, 568-574.
- 828 Rolls, B. J., Fedoroff, I. C., & Guthrie, J. F. (1991). Gender differences in eating behavior
829 and body weight regulation. *Health Psychology*, *10*, 133-142.
- 830 Rush, S., & Driscoll, D. A. (1968). Current Distribution in the Brain From Surface Electrodes.
831 *Anesthesia & Analgesia*, *47*.
- 832 Sedgmond, J., Lawrence Natalia, S., Verbruggen, F., Morrison, S., Chambers Christopher,
833 D., & Adams Rachel, C. (2019). Prefrontal brain stimulation during food-related
834 inhibition training: effects on food craving, food consumption and inhibitory control.
835 *Royal Society Open Science*, *6*, 181186.
- 836 Stagg, C. J., Antal, A., & Nitsche, M. A. (2018). Physiology of Transcranial Direct Current
837 Stimulation. *The Journal of ECT*, *34*.
- 838 Thair, H., Holloway, A. L., Newport, R., & Smith, A. D. (2017). Transcranial Direct Current
839 Stimulation (tDCS): A Beginner's Guide for Design and Implementation. *Frontiers in*
840 *Neuroscience*, *11*, 641.
- 841 Tremblay, S., Lepage, J.-F., Latulipe-Loiselle, A., Fregni, F., Pascual-Leone, A., & Théoret,
842 H. (2014). The Uncertain Outcome of Prefrontal tDCS. *Brain Stimulation*, *7*, 773-783.
- 843 Vitor-Costa, M., Okuno, N. M., Bortolotti, H., Bertollo, M., Boggio, P. S., Fregni, F., &
844 Altimari, L. R. (2015). Improving Cycling Performance: Transcranial Direct Current
845 Stimulation Increases Time to Exhaustion in Cycling. *PLOS ONE*, *10*, e0144916.
- 846 Wardle, R. A., Thapaliya, G., Nowak, A., Radford, S., Dalton, M., Finlayson, G., & Moran, G.
847 W. (2018). An Examination of Appetite and Disordered Eating in Active Crohn's
848 Disease. *Journal of Crohn's and Colitis*, *12*, 819-825.
- 849 World Health Organisation. (2020). *Obesity and Overweight*. <[https://www.who.int/en/news-
850 room/fact-sheets/detail/obesity-and-overweight](https://www.who.int/en/news-room/fact-sheets/detail/obesity-and-overweight)> Accessed 29 July 2020.
- 851 Zheng, H., Huang, D., Chen, S., Wang, S., Guo, W., Luo, J., Ye, H., & Chen, Y. (2016).
852 Modulating the Activity of Ventromedial Prefrontal Cortex by Anodal tDCS Enhances
853 the Trustee's Repayment through Altruism. *Frontiers in Psychology*, *7*, 1437.

854 Zheng, H., Wang, S., Guo, W., Chen, S., Luo, J., Ye, H., & Huang, D. (2017). Enhancing the
855 Activity of the DLPFC with tDCS Alters Risk Preference without Changing
856 Interpersonal Trust. *Frontiers in Neuroscience*, 11, 52.
857