

1 **Effective transcranial direct current stimulation (tDCS) parameters for the modulation**  
2 **of eating behavior: A systematic literature review and meta-analysis**

3

4 **Running title:** Effective tDCS parameters for eating behavior

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## 25 **ABSTRACT**

### 26 *Objective*

27 To consider the effect of differing transcranial direct current stimulation (tDCS) parameters  
28 on eating-related measures, and how issues with experimental design (e.g., inadequate  
29 blinding) or parameters variation may drive equivocal effects.

30

### 31 *Methods*

32 Literature searches were conducted across MEDLINE, PsycINFO, Scopus, and Science  
33 Direct. Studies using conventional sham-controlled tDCS to modify eating-related measures  
34 in adult human participants were included. A total of 1,135 articles were identified and  
35 screened by two independent authors. Study quality was assessed using the Risk of Bias  
36 tool. Random-effect meta-analyses were performed, with subgroup analyses to determine  
37 differences between parameter sets.

38

### 39 *Results*

40 We identified 28 eligible studies; seven showed low risk of bias, with the remaining studies  
41 showing bias arising from issues implementing or reporting blinding protocols. Large  
42 variation in applied parameters was found, including montage, current intensity and density,  
43 participant and researcher blinding, and the use of online or offline tasks. The application of  
44 differing parameters appeared to alter the effects of tDCS on eating-related measures,  
45 particularly for current density ( $g = -0.25$  to  $0.31$ ), and when comparing single-session ( $g = -$   
46  $0.08$  to  $0.01$ ) versus multi-session protocols ( $g = -0.34$  to  $-0.29$ ). Some parameters result in  
47 null effects.

48

### 49 *Conclusion*

50 The absence of tDCS-mediated change in eating-related measures may be driven by  
51 variation in applied parameters. Consistent application of parameters which appear effective  
52 for modulating eating behavior is important for identifying the potential impact of tDCS. Using

53 the findings of this review, we propose a series of parameters that researchers should apply  
54 in their work.

55

## 56 **KEYWORDS**

57 Appetite, Food consumption, Food craving, Food reward, Neuromodulation, Non-invasive  
58 brain stimulation

59

## 60 **ACRONYMS**

61 CI = confidence interval; cm = centimeter; COMT = catechol-o-methyl transferase; DLPFC =  
62 dorsolateral prefrontal cortex; EBA = extrastriate body area;  $g$  = Hedges'  $g$ ; IFG = inferior  
63 frontal gyrus; mA = milliampere; NIBS = non-invasive brain stimulation; PFC = prefrontal  
64 cortex; PICO = Population, Intervention, Control and Outcome; PRISMA = Preferred  
65 Reporting Items for Systematic Reviews and Meta-Analyses; RoB = risk of bias; SD =  
66 standard deviation; SE = standard error; tDCS = transcranial direct current stimulation; tnM1  
67 = tongue muscle representation of the primary motor cortex

68

## 69 1. INTRODUCTION

70 Over the last decade there has been increasing interest in the use of non-invasive brain  
71 stimulation (NIBS) techniques, particularly transcranial direct current stimulation (tDCS), for  
72 modifying eating behaviors associated with overconsumption and weight gain. Through  
73 tDCS, a constant weak electrical current is applied to the brain via electrodes connected to a  
74 battery-powered device (1, 2). Although the current strength is not sufficient to cause  
75 neuronal firing, it appears able to modulate resting membrane potentials in a polarity-  
76 dependent manner through inhibition of neurotransmitters such as gamma-aminobutyric acid  
77 and glutamate (3, 4). The electric current is delivered through an anode (positive charge)  
78 electrode, where it is passed through the brain to a cathode (negative charge) electrode and  
79 is returned to the device. In a simplistic view, the anode is associated with depolarization of  
80 cortical activity and an increased likelihood of spontaneous neuronal firing. Conversely, the  
81 cathode is associated with hyperpolarization of the cortex resulting in the decreased  
82 likelihood of spontaneous neuronal firing (3).

83

84 The ability of tDCS to alter eating behaviors, such as food craving and consumption, has  
85 been of great interest for researchers due to its potential use in the treatment of obesity (5).  
86 Since the first study using tDCS to alter food craving was published over a decade ago (6),  
87 the potential for this technique to improve hedonic appetite control has seen an increase in  
88 published data. However, despite the promising effects outlined in this early study, more  
89 recent data shows equivocal effects (7-10). This may be due to a lack of replication of data  
90 as studies have employed varying designs (e.g., between- and within-group design),  
91 outcome measures and stimulation parameters. The modulatory effects of tDCS are driven  
92 largely by the specific stimulation parameters and device set-up (11). This includes the  
93 electrode montage, current intensity and density, stimulation duration, and number of  
94 sessions. Online protocols may also impact the modulatory effects (12). Despite the evident  
95 variation caused by altering stimulation parameters, these parameters can vary greatly  
96 between studies resulting in large variation in data (4, 13). This demonstrates the importance

97 of identifying and consistently applying parameters that are known to modulate the outcome  
98 measure. This is not a new concept (3, 12, 14), but has not been discussed in-depth for  
99 studies measuring eating-related outcomes.

100

101 Understanding the ability of tDCS to modify eating behaviors is particularly difficult with  
102 variation in study design, outcome measures and stimulation parameters. If indeed this  
103 technique is to be used as an additional or adjunctive treatment modality for weight  
104 management, it is important that these inconsistencies are addressed (15). Here we expand  
105 on recent reviews (16, 17) to provide further detail on the potential impact of different  
106 stimulation parameters and widen the discussion to incorporate important parameter  
107 considerations, including reference electrode placement, electrode size, current density,  
108 blinding efficacy, and the use of offline/online protocols. Specifically, we aim to identify  
109 effective tDCS parameter ranges for the modulation of eating behavior, and determine  
110 whether null effects are driven by parameters outside of these ranges.

111

## 112 **2. METHODS**

### 113 ***2.1. Search Strategy***

114 An electronic literature search was performed in line with the Preferred Reporting Items for  
115 Systematic Reviews and Meta-Analyses (PRISMA) (18) (Table S1). The literature search  
116 was completed using MEDLINE, PsycINFO and Scopus databases in March 2019, and  
117 repeated in July 2020 to include additional articles published during this time. Search terms  
118 are displayed in Table 1. An additional search was conducted using the Science Direct  
119 database. Due to restrictions on Boolean terms and wildcards (\*), revised search terms were  
120 used (Table 1). Results were limited to those written in English and published after 1998 to  
121 coincide with the development of modern tDCS procedures (2, 19).

122

123

\*\*\* INSERT TABLE 1 HERE \*\*\*

124

## 125 **2.2. Inclusion and Exclusion Criteria**

126 After removing duplicates (n = 248), titles and abstracts were assessed for inclusion. Where  
127 elimination based on title and abstract was not possible, full-text articles were retrieved and  
128 assessed for inclusion in the final sample. Reviews, abstracts (where full-text articles were  
129 unavailable), editorials/commentaries, book chapters, theses, study protocols, case reports  
130 and animal studies were not included in the present review (total n = 68). Articles were  
131 assessed in line with the Population, Intervention, Criteria and Outcome (PICO) model (20).  
132 Articles were included if they were peer-reviewed intervention studies that recruited adult  
133 human participants (*population*), applying conventional tDCS (i.e., one anode, one cathode)  
134 procedures (*intervention*) which were sham-controlled (*control*), and reported an outcome  
135 measure relating to eating behavior (food craving, food consumption, food reward, subjective  
136 appetite) (*outcome*). Article selection was performed by two independent authors (JDB and  
137 DS). Any further articles known to the authors were also considered for inclusion.

138

## 139 **2.3. Data Extraction**

140 For each eligible study, the following data were extracted: names of authors; year of  
141 publication; participant characteristics; montage and electrode size; current intensity and  
142 density; stimulation duration; ramp duration; sham protocol; number of sessions; blinding  
143 efficacy; use of online and offline protocols; outcome measures; main findings. Data were  
144 extracted as reported in the original article(s) by JDB.

145

## 146 **2.4. Study Quality Assessment**

147 The quality of studies was determined using the Cochrane Collaboration's Risk of Bias  
148 (RoB) tool (21). Judgements were made by two independent authors at the study level;  
149 agreement between authors (JDB and NCS) was high ( $\kappa = 0.93$ ). This data will be used to  
150 identify issues with study design, particularly in relation to the delivery of tDCS.

151

## 152 **2.5. Meta-Analysis**

153 Means, standard deviations (SD) and sample size were extracted for eating-related  
154 measures. Where standard error (SE) was reported, SD was estimated using the equation  
155  $SD = SE \times \sqrt{n}$  (20). If data were not reported, datasets were requested from corresponding  
156 authors. Otherwise, means and SD or SE were extracted from available figures using  
157 WebPlotDigitizer (version 4.4) (22), or estimated using the Practical Meta-Analysis Effect  
158 Size Calculator (23) by entering  $t$  or  $F$  statistic and sample size. If data or effect sizes were  
159 estimated, these were validated by two authors independently (JDB and NCS). Standardized  
160 mean differences were calculated and adjusted using Hedges'  $g$  due to small sample size ( $n$   
161  $< 20$ ) across many of the reviewed articles.

162

163 Analyses focused on single-session tDCS, to remove the potential cumulative effect of multi-  
164 session protocols. Four studies did not measure the effects of single-session tDCS and were  
165 removed from analyses (24-27). Additional studies were removed due to missing data (28)  
166 or due to all participants receiving active tDCS (29). To reduce confounding analyses, the  
167 expectation effect observed by Ray et al. (30) was also removed. A total of 21 studies ( $n =$   
168 743 participants) were included in the meta-analysis (Table S5). Where possible, separate  
169 analyses comparing single- versus multi-session tDCS were completed to identify any  
170 cumulative effect (additional  $n = 3$  studies, 105 participants). Where effect sizes are based  
171 on composite scores (i.e., mean scores across varying levels of a specific parameter) within  
172 the same participant group, these were removed from analyses for the specific parameter  
173 measure to avoid confounding analyses (31, 32).

174

175 Differences in comparisons within experiments, journal articles, and research groups can  
176 result in dependent effect sizes leading to narrow confidence intervals (CI) and small  
177 estimates of SE (33, 34). We completed multilevel modelling to account for such  
178 dependencies, with separate levels for comparisons within participant samples, experiments  
179 within studies, and studies within the same research group. As indicated by Akaike

180 information criteria and likelihood ratio test results, the addition of each level did not  
181 improve model fit (Table S3).

182

183 Meta-analyses were performed using R (35) with the meta package (36). Due to the  
184 variability in study design and outcomes, random effects models were used. Effect sizes  
185 were interpreted as trivial ( $g < 0.20$ ), small ( $g = 0.20$ ), moderate ( $g = 0.50$ ) or large ( $g > 0.80$ )  
186 (37). A negative effect size favors active tDCS, indicating that active protocols reduce the  
187 outcome measure. In comparison, positive effect sizes would indicate an increase in the  
188 measure following active versus sham tDCS, favoring sham tDCS. Effect size heterogeneity  
189 was assessed using the  $I^2$  index, and interpreted as might not be important (0 to 40%), may  
190 represent moderate heterogeneity (30 to 60%), may represent substantial heterogeneity (50  
191 to 90%), and may represent considerable heterogeneity (75 to 100%) (38). To test for  
192 publication bias, Egger's regression was used (39). Subgroup analyses were conducted to  
193 identify potential moderating effects of tDCS parameters on outcome measures. Where a  
194 meta-analysis was not possible, a systematic literature review is included.

195

### 196 **3. RESULTS**

197 In this section we provide the results of the review and discuss the findings. A total of 1,135  
198 articles were identified, and after removing duplicates and assessing eligibility, 28 articles  
199 were included in the present review (Figure S1). All reviewed studies used conventional  
200 tDCS procedures and were sham-controlled trials, with 12 between-participant and 16  
201 within-participant studies. A total of 996 participants were recruited across the reviewed  
202 studies, ranging from 9 to 172 individuals per study, and included individuals with healthy  
203 weight ( $n = 14$  studies, 576 participants), overweight or obesity ( $n = 15$  studies, 393  
204 participants). Ljubisavljevic et al. (29) included individuals with healthy weight or overweight,  
205 but do not provide total  $n$  for each weight category.

206



207 Most studies recruited individuals classed as “healthy”, which refers to a lack of medical or  
208 behavioral conditions and is irrespective of weight status. A small number of studies  
209 recruited participants with specific conditions, such as Prader Willi Syndrome (40), Catechol-  
210 O-methyl transferase (COMT) Val158Met polymorphism (26, 27), frequent food cravings (6,  
211 7, 41, 42), restrained eating (43, 44), binge eating disorder (45, 46), and anorexia or bulimia  
212 nervosa (47, 48). Heterogeneity across studies ( $I^2$  range = 0 to 45%) suggests it might not  
213 be important (Table S4). Funnel plots show good symmetry across measures (Figure S4),  
214 with Egger’s regression suggesting little evidence of publication bias ( $p > 0.08$ ). A summary  
215 of the meta-analytic data and forest plots are available in the Supplemental Digital Content.

216

### 217 **3.1. Study Quality**

218 Only 7 of the 28 studies showed low risk of bias across all domains, and therefore an overall  
219 low risk of bias. Across the remaining studies, insufficient detail around participants and  
220 researcher blinding was the greatest source of bias, particularly the process in which  
221 researcher blinding was upheld. This also affected risk of bias judgement for the  
222 measurement of outcome and selection of reported results. Most studies ( $n = 18$ ) maintained  
223 a double-blind protocol, either through the use of a pin-protected stimulation device or an  
224 independent researcher completing stimulation protocols. Seven studies used a single-blind  
225 design, with a further three studies providing insufficient detail around blinding protocols.

226

227 Additional bias arose due to the post-randomization exclusion of participants ( $n = 14$   
228 studies). Many studies do not provide a sample size calculation, which makes it difficult to  
229 identify the impact of these exclusions. The exclusion of participants is particularly  
230 problematic where this leads to a relatively small sample size, which is an important  
231 consideration due to the repeated use of small sample size across tDCS research (14, 49,  
232 50). Ray et al. (30) included a source of intended bias around participant blinding, with the  
233 aim of assessing the impact of expecting to receive active versus sham tDCS on eating-  
234 related measures. Although this study received an overall high risk of bias, the study was

235 high-quality and this source of bias provides important considerations around the information  
236 shared with participants. The RoB assessment is summarized in the Supplemental Digital  
237 Content (Figures S2 and S3).

238

### 239 **3.2. Montage**

240 The most common target location is the right dorsolateral prefrontal cortex (DLPFC) ( $n = 17$ ),  
241 with a smaller proportion of studies targeting the left DLPFC ( $n = 8$ ) (Table 2). This cortical  
242 region is of interest due to its role in executive functioning, a process associated with the  
243 control of reward-driven appetite through the increase in inhibitory control and curbing of  
244 impulsive behaviors (51, 52). Where the anode was placed over the right DLPFC and  
245 cathode over the left DLPFC, a reduction across measures was seen ( $g = -0.39$  to  $0.01$ )  
246 (Figures S5 to S10). Less consistent patterns were found when both anode and cathode  
247 electrodes are placed over alternative cortical regions, although effect sizes are often based  
248 only on single studies (Figures S5 to S10; Table S2). The right DLPFC is of particular  
249 interest as reduced activity of this region is associated with poor control of dietary behaviors  
250 and obesity (53). The consistent negative effect sizes across eating-related measures when  
251 targeting the right DLPFC may lend support for this right brain hypothesis of obesity (53).

252

253 **\*\* INSERT TABLE 2 HERE \*\***

254

255

256 Many studies delivering tDCS across other cortical regions also measured effects when  
257 targeting the right DLPFC. Composite scores were calculated for these studies, to retain one  
258 effect size per participant group and avoiding increasing homogeneity (31), and as such  
259 were removed from analyses. However, the results of these studies provide further support  
260 for targeting the right DLPFC. For example, Carvalho et al. (54) found increased preference  
261 for chocolate following anode left/cathode right DLPFC stimulation, when compared with  
262 both anode right/cathode left DLPFC and sham protocols. The authors also found craving

263 intensity was reduced to a greater extent by anode right/cathode left montages compared  
264 with anode left/cathode right DLPFC stimulation; replicating findings by Fregni et al. (6).

265

266 Further studies targeting the left DLPFC failed to identify a change in measures of subjective  
267 appetite, food craving or food consumption (26, 27). Additionally, Marron et al. (55) found  
268 increased hunger and desire to eat when applying 2.0 milliampere (mA) for 20 minutes with  
269 the anode over the left DLPFC and cathode over the cerebellum. Targeting the left DLPFC  
270 appears to have minimal effect on eating-related measures and suggests greater importance  
271 for targeting the right versus left DLPFC, providing further support for the right brain  
272 hypothesis (53). However, not all studies have found an effect of tDCS when applied to the  
273 right DLPFC (Figures S5 to S10). This may be due to the eating behavior traits of the  
274 recruited participants, with these studies recruiting individuals who do not display a  
275 susceptibility to overconsumption and are likely able to appropriately inhibit impulsive  
276 behaviors through effective executive control. In comparison, an effect is more consistently  
277 shown in those with frequent food cravings or binge-type behaviors (6, 7, 41, 42, 45, 46).  
278 This highlights a potential behavior trait-dependent effect of tDCS (56).

279

280 Novel target locations include the right inferior frontal gyrus (IFG) (43, 44), medial prefrontal  
281 cortex (PFC) (48), right extrastriate body area (EBA) (48), and the primary motor cortex  
282 representation of the tongue muscle (tnM1) (57) (Figure 1). These regions are additionally  
283 associated with consumptive behaviors, however data following the use of these more novel  
284 montages show no significant stimulation effects or an increase in measures of food  
285 consumption and implicit preference (44, 48). The IFG and medial PFC are in anatomically  
286 close proximity to the DLPFC, and the large electrodes used in these studies are likely to  
287 overlap the DLPFC. However, these alternative montages likely change the current  
288 distribution when compared to DLPFC-targeted stimulation (58). The effects of tDCS may be  
289 dependent on the current entering the DLPFC, specifically the right hemisphere, and so the  
290 small amount of current potentially entering through close proximity with an alternative target

291 region may be insufficient to cause any meaningful modulation. This further suggests the  
292 DLPFC is an important focal target for the modulation of eating behaviors.

293

294 **\*\* INSERT FIGURE 1 HERE \*\***

295

296 In addition to variation in target location, researchers opt for different reference electrode  
297 locations. Across the included studies, the reference electrode was placed bilaterally to the  
298 target electrode (i.e., over the same cortical region, but on the opposite hemisphere; e.g.,  
299 right and left DLPFC), over the contralateral supraorbital region (i.e., above the eye on the  
300 opposite hemisphere; e.g., right DLPFC and left supraorbital region), or over the occipital  
301 lobe or cerebellum (Figure 1). A comparison of the potential effects of different reference  
302 electrode positions on eating behaviors has not been conducted, and it is difficult to fully  
303 identify any potential impacts. Moving the reference electrode to alternative locations is likely  
304 to alter the current distribution, and may affect the expected tDCS-induced effects (58, 59).  
305 While there are similar reductions in eating-related measures when comparing tDCS with the  
306 same target location but differing reference electrode positions (e.g., left DLPFC versus left  
307 supraorbital region) (6, 7, 40-42, 45, 60), there was variation in effect sizes (Table S2).  
308 Again, these analyses should be interpreted with caution as the overall effect sizes are often  
309 based on single-studies and are likely driven by other variables.

310

311 One way to minimize the physiological impact of the reference electrode is to place it over an  
312 extracephalic region, that is over a region of the body that is not the cortex (61). One study  
313 placed the reference electrode over the contralateral cheek (43), and three studies placed  
314 this electrode on a section of the participant's arm or shoulder (10, 29, 46). The advantage of  
315 these extracephalic montages is that the physiological effects of the reference electrode are  
316 minimized (62, 63), however this may be at the expense of altering the direction and  
317 distribution of the electric current (14, 61). Despite these effects, placing the reference  
318 electrode over an extracephalic region did not appear to impact the effects of tDCS on

319 behavioral measures as observed when using cephalic montages, with comparable effect  
320 sizes following cephalic versus extracephalic montages (Table S2; Figures S11 to S16).

321

322

### 323 **3.3. Current Intensity and Current Density**

324 The most consistently applied current intensity is 2.0 mA, delivered across 23 of the 28  
325 studies. One study applied 1.5 mA (43), and 5 studies delivered 1.0 mA (9, 46, 48, 57, 60). It  
326 has been suggested that 2.0 mA is the minimum intensity required to elicit changes in  
327 eating-related measures (17, 32). However, since the publication of these papers, Chen et  
328 al. (43) applied 1.5 mA and found improved reaction times in a stop-signal task. This  
329 intensity warrants further investigation, especially in light of the potential issues surrounding  
330 blinding efficacy at higher current intensities (64) (see 3.5). Unlike the earlier meta-analyses,  
331 the present analysis found comparable effects of differing current intensities when  
332 incorporating more recently published work (Figures S17 to S22).

333

334 It could be that, rather than current intensity, the effects of tDCS are driven more by the  
335 density of applied current (i.e., the amount of current delivered per unit area [ $\text{mA}\cdot\text{cm}^{-2}$ ]), as  
336 low current densities will likely diminish the effect of stimulation on the underlying cortex (3).

337 The suggested minimum intensity of 2.0 mA equates to a minimum current density between  
338 0.057 and 0.080  $\text{mA}\cdot\text{cm}^{-2}$ , in line with commonly used electrode sizes of 25 and 35  $\text{cm}^2$ .

339 Indeed, this appears to be the boundary within which tDCS is able to modulate measures of  
340 eating behavior (Figures S23 to S28). In particular, 0.057  $\text{mA}\cdot\text{cm}^{-2}$  resulted in a consistent  
341 reduction (i.e., favoring active tDCS) across all measures ( $g = -0.25$  to  $-0.06$ ). As

342 comparable current densities are achieved through varying current intensities and electrode  
343 sizes, this may explain why we were unable to replication the intensity-dependent effect (17).

344

345 Maintaining a comparable current intensity, and therefore current density, does not occur in  
346 all studies. Four studies applied 1.0 mA using large 35  $\text{cm}^2$  electrodes, resulting in a current

347 density of  $0.029 \text{ mA}\cdot\text{cm}^{-2}$  (9, 46, 57, 60). These studies failed to find an effect of stimulation  
348 across measures of hunger and food craving, with the exception of Jauch-Chara et al. (60)  
349 who identified reduced food consumption following repeated sessions of active tDCS,  
350 potentially due to a cumulative effect (60) (see 3.7).

351

### 352 **3.4. Stimulation Duration**

353 Stimulation was applied for 15 minutes ( $n = 1$ ), 20 minutes ( $n = 23$ ), 30 minutes ( $n = 3$ ), and  
354 40 minutes ( $n = 2$ ) across the reviewed studies. Vicario et al. (57) delivered 15 minutes of  
355 1.0 mA stimulation to the left tnM1, which failed to change subjective hunger scores. All  
356 studies that used stimulation durations greater than 20 minutes also used multi-session  
357 protocols, where tDCS was delivered over subsequent days (10, 25-27, 40) (see 3.7).

358 Comparison of effects following single-session tDCS as part of these multi-session designs  
359 is largely not reported, and so the effects of longer stimulation durations in a single-session  
360 design cannot be made. Such extended durations should be used with caution, as data from  
361 motor cortex stimulation suggests that longer durations may lead to a reversal of the  
362 expected effect (65, 66). There are no recorded studies to date that have compared the  
363 effects of stimulation duration on eating behavior outcomes, and further studies utilizing  
364 shorter (10 to 15 minutes) durations are required as this would reduce the time requirement  
365 of participants.

366

### 367 **3.5. Sham Protocols and Blinding**

368 Commonly applied sham protocols involve the current being ramped up to the desired  
369 intensity and then delivered for 0 to 120 seconds before being ramped down (Figure 2). To  
370 imitate both the incremental and decremental currents integral to active tDCS protocols,  
371 some studies deliver the aforementioned ramping protocol at the start and end of the  
372 stimulation period. The common cutaneous sensations associated with delivery of the direct  
373 current typically occur at the start of current delivery (i.e., the ramp period) and often  
374 habituate within the initial seconds of stimulation (67). Therefore, sham protocols are

375 considered effective methods of participant blinding as they mimic the initial phase of active  
376 tDCS, but are unlikely to result in lasting modulation of the cortex due to the short duration  
377 (67-69). Although standardized sham protocols are generally assumed to be effective,  
378 researchers may struggle to maintain blinding at higher current strengths due to the more  
379 pronounced cutaneous sensations (64).

380

381

**\*\* INSERT FIGURE 2 HERE \*\***

382

383 Only 12 studies included quantitative data on the effectiveness of sham protocols, with  
384 participants' ability to correctly guess the condition received ranging from 17 to 97%  
385 (Cohen's  $d = 0.33$  to  $0.58$ ). Of these studies, participants were unable to identify active  
386 stimulation above the level of chance across 6 studies (9, 10, 29, 47, 54, 70). Many of these  
387 studies utilized 2.0 mA, suggesting that participant blinding can be achieved at higher  
388 current strengths. Two further studies report successful participant blinding, but do not  
389 provide data to support this (25, 42). The remaining studies reported failure to achieve  
390 adequate participant blinding, with correct guesses ranging from 60 to 97% (7, 8, 43, 44, 46,  
391 48). Again, these studies oppose the notion that higher current intensities result in poorer  
392 participant blinding, as they include 1.0 and 1.5 mA protocols.

393

394 Based on the overall correct guess rate (i.e., number of participants able to identify active  
395 and sham protocols), there are considerable differences in effect sizes when comparing  
396 successful and unsuccessful blinding protocols. Where blinding was upheld, trivial-to-small  
397 positive effect sizes were observed ( $g = 0.05$  to  $0.31$ ) (Figures S29 to S34). In comparison,  
398 studies with unsuccessful tDCS blinding resulted in more consistent negative effect sizes,  
399 particularly across measures of explicit wanting, food craving and hunger ( $g = -0.16$  to  $-0.11$ )  
400 (Figures S29 to S34). Fassi and Cohen Kadosh (71) suggest, rather than focusing on overall  
401 correct guess rate, we should instead assess active guess rate (i.e., percentage of  
402 participants able to correctly guess receiving active protocols). The authors argue that

403 overall correct guess rate can lead to misleading estimate of blinding success (72). Across  
404 the reviewed literature, overall correct guess rate suggests participant blinding may be  
405 upheld (mean 48%, range 17 to 79%) whereas active guess rate demonstrates that  
406 participants are consistently able to identify active protocols (mean 73%, range 60 to 85%).

407

408 In addition, the effects of researcher blinding cannot be ignored. When comparing the effects  
409 of single- and double-blind study designs on tDCS modulation of eating behavior, variation in  
410 effect sizes is evident (Figures S35 to S40). In particular, the reduction in food consumption  
411 and explicit wanting following tDCS appear to be driven by studies utilizing single-blind  
412 design. Discrepancy in effect sizes further emphasizes the importance of implementing and  
413 maintaining a double-blind study design.

414

### 415 **3.6. Offline versus Online Protocols**

416 Offline protocols typically involve the participant remaining seated and relaxed with tDCS  
417 delivered without distraction. In comparison, online protocols employ specific tasks during  
418 the stimulation period, such as cognitive training (14). Many of the studies in this review  
419 used offline protocols ( $n = 20$ ). Eight studies applied online tDCS, where participants  
420 watched unrelated media (e.g., nature documentary, cartoon) (10, 48), completed a food-  
421 related task (e.g., food choice computer-based task) (7, 9, 46, 73), or completed a cognitive  
422 task (e.g., approach-avoidance training, Go/No-Go task) (8, 54). Variation in effect sizes is  
423 evident when comparing offline and online protocols (Figures S41 to S46). Where offline  
424 protocols produce a more consistent trivial-to-small negative effect size ( $g = -0.31$  to  $0.12$ ),  
425 with the exception of hunger measures, there is greater variation in the effects following  
426 online protocols ( $g = -0.16$  to  $0.15$ ).

427

### 428 **3.7. Number of Stimulation Sessions**

429 A total of 9 studies included repeated sessions of active or sham tDCS, ranging from 3 to 16  
430 sessions. These multi-session studies appeared to result in a cumulative effect, with small



431 effect sizes for measures of food craving ( $g = -0.29$ ; 95% CI = -0.60 to 0.03) and food  
432 consumption ( $g = -0.34$ ; 95% CI = -1.03 to 0.35), compared to only trivial effect sizes  
433 following single session tDCS ( $g = -0.08$  to 0.01) (Figure 3).

434

435 **\*\* INSERT FIGURE 3 HERE \*\***

436

#### 437 **4. Discussion**

438 The findings of the review related to specifics of the studies and relevant parameters are  
439 discussed above. In this section, we provide a general discussion of the findings with further  
440 consideration of specific parameters. In this review we have considered the impact of a  
441 range of stimulation parameters, and what methodological issues may explain the observed  
442 inconsistencies in data. Figure 4 captures the variation in applied tDCS parameters across  
443 the reviewed research. While our meta-analyses were unable to capture all parameter  
444 variation, they have identified parameters that appear to modulate eating behavior. We  
445 argue that a more holistic and comprehensive consideration of these parameters is required  
446 to identify a consistent effect of tDCS protocols on eating-related measures. In Table 3 we  
447 propose a range of tDCS parameters that appear to be most effective for modulating eating  
448 behaviors. This is not intended as an absolute recommendation, but as a point of reference  
449 and to help further discuss the most effective parameters for eating-related studies. In  
450 addition to these, researchers should adhere to a double-blind protocol with a within-  
451 participant (randomized and counterbalanced) design, particularly for single-session studies  
452 and where this fits the study aims. We also suggest that studies provide sufficient detail on  
453 the study design and implemented tDCS parameters so the effects of parameter sets can be  
454 fully understood. Protocols using parameters known to affect the outcome, such as online  
455 tasks, should be carefully considered with a clear justification for their use.

456

457 **\*\* INSERT FIGURE 4 HERE \*\***

458

**\*\* INSERT TABLE 3 HERE \*\***

459

460 As discussed above, current density may be a more important driver of tDCS effects than  
461 current intensity. Lower current intensities, such as 1.0 mA, can be utilized whilst maintaining  
462 current densities in line with 2.0 mA protocols. For example, for 1.0 mA protocols the  
463 electrode size can be reduced to between 12.5 and 17.5 cm<sup>2</sup>, resulting in current densities  
464 between 0.057 and 0.080 mA·cm<sup>-2</sup>. It should be noted that increasing the current density is  
465 unlikely to lead to linear effects on the underlying cortex and outcome measures, but greater  
466 current densities may provide more consistent effects (61, 74). Animal models suggest  
467 tissue damage occurs at current densities above 25 mA·cm<sup>-2</sup> (75); to maintain participant  
468 safety, current density should not exceed this threshold (76).

469

470 When considering the specific tDCS parameters, and the potential impact these may have  
471 on behavior, the reference electrode should not be ignored as it is probable that this  
472 electrode exerts some physiological effect on the cortex which will likely affect outcome  
473 measures (3, 58). Therefore, careful consideration of the placement of both electrodes is  
474 required, with the reference electrode placed over a region unrelated to the outcome  
475 measure (14). It is assumed that increasing the distance between electrodes results in a  
476 greater amount of the current entering the brain, as opposed to being shunted across the  
477 scalp (58). However, many studies place the target and reference electrodes relatively close  
478 together, such as bilaterally over the DLPFC (6, 7).

479

480 The effect of increasing electrode distance on measures of eating behavior is not clear. The  
481 ability of extracephalic montages to increase the amount of current penetrating deeper brain  
482 structures is also unclear (77, 78), although they do appear able to reduce the amount of  
483 current being shunted across the scalp (61, 79). If extracephalic montages are able to  
484 increase the amount of current reaching deeper brain structures, this may be important for  
485 reaching those structures involved in rewarding components of eating behavior, such as the  
486 nucleus accumbens (80). Further research that includes neuroimaging techniques is needed

487 to support this premise. If an extracephalic montage is used, there should be careful  
488 consideration of other parameters; for example, higher current intensities may be required to  
489 compensate for the greater distance between electrodes (81).

490

491 Reflecting on the issues raised with reference electrode placement (see 3.20), any  
492 modulatory effect of the reference electrode may be diminished by using a large electrode  
493 size. Electrodes are typically equal size of 25 or 35 cm<sup>2</sup>, but range from 16 to 70 cm<sup>2</sup>. When  
494 electrodes are equal size there is similar cortical neuromodulation (with opposite polarity)  
495 under both electrodes. In comparison, when the size of one electrode is increased, the  
496 current density is reduced under that electrode which results in modulation under the smaller  
497 electrode area only (82). Two studies have used larger reference electrodes (48, 70).

498 Although these studies do not show improvements in eating-related measures, this again  
499 may be driven by methodological issues such as the use of an online task (48) (see 3.6).

500 The use of large reference electrode size in eating behavior studies, especially with offline  
501 protocols, is yet to be fully determined. Large reference electrodes can alter the current  
502 distribution and may reduce the deleterious effects associated with the cathode (83).

503 Increasing reference electrode size should be combined with the use of greater distances  
504 between electrodes, such as extracephalic montages, to minimize the chance of current  
505 shunting across the scalp (79, 84).

506

507 The effects of tDCS are brain state-dependent and can be shaped by the use of online  
508 protocols (3, 15). Offline protocols lead to modifications of cortical activity that last beyond  
509 the stimulation duration, whereas the use of online tasks leads to modulation of cortical  
510 activity related to the specific task (1, 85). Additionally, the use of an unrelated online task  
511 may impact the expected polarity-dependent effects of tDCS (14). This may explain the lack  
512 of expected effects on eating-related measures across the reviewed studies that use online  
513 protocols. Even where a food-based training task is used to modify food choice behavior,  
514 these studies typically measure wider eating-related measures such as food craving and

515 consumption (9, 73). Although food choice is an important driver of food consumption, food  
516 cravings are a more influential predictor of dietary intake and focusing on tasks promoting  
517 the regulation of food cravings may provide more fruitful effects (86)

518

519 It is currently unclear which participant populations may benefit from the use of online  
520 protocols (74, 87, 88), and many studies fail to sufficiently justify the use of these protocols.  
521 Where tDCS is delivered alongside a cognitive training task there appears to be improved  
522 performance relating to the specific task, which highlights the importance of employing an  
523 online task that is specific to the outcome measure of interest (88, 89). The impact of online  
524 tasks on the direction of stimulation effects and outcome measures warrants careful  
525 consideration of their use, but it may prove beneficial to use online protocols to enhance the  
526 modulatory effects of tDCS on specific eating-related measures. However, the online tasks  
527 performed in the reviewed studies are not always eating behavior-specific, and typically  
528 focus on improving cognitive functions (8, 54). This may lead to improvements in the  
529 cognitive measure, at the expense of improving eating behavior scores (85).

530

531 Gluck et al. (10) performed tDCS while participants watched nature or history documentaries  
532 and they were able to show reduced consumption of fats and soda when comparing anodal  
533 versus cathodal stimulation. This suggests the use of unrelated media with the aim diverting  
534 thoughts away from food may prove a valuable procedure for standardizing participants'  
535 thoughts during tDCS delivery. Until a clear effect of tDCS on eating behaviors is  
536 consistently reported or a clear impact of online protocols on eating-related measures can be  
537 identified, online protocols should be used with caution and a clear justification for their  
538 inclusion should be provided.

539

540 Across the reviewed studies, stimulation was typically applied daily, with four studies initially  
541 applying stimulation with a 24-hour interval and increasing this to 48 hours in the second  
542 stage of the study (e.g., from inpatient to outpatient treatment) (24-27). Although a 48-hour

543 interval is likely to negate the cumulative effects of stimulation (90), it is possible that  
544 increasing the interval to 48 hours following initial daily stimulation could strengthen the  
545 modulatory effects. However, studies that implement this protocol failed to identify any  
546 change in subjective appetite or food craving scores (24-27), but this may be due to their  
547 focus on left DLPFC stimulation or longer stimulation durations. This poses an important  
548 consideration for multi-session designs; whether daily sessions of stimulation are required,  
549 or if the number of sessions can be reduced later in the study to minimize the time  
550 requirements of participants. Again, further data are required to determine the impact of daily  
551 to second-daily stimulation protocols, which should adhere to effective parameters.

552

553 There appears to be the potential for repeated session to negate the deleterious effects  
554 when parameters are below the proposed effective range, as discussed in the above  
555 sections. For example, Jauch-Chara et al. (60) used low current intensity (1.0 mA) and  
556 density ( $0.029 \text{ mA}\cdot\text{cm}^{-2}$ ), but they were able to demonstrate an ability of anodal tDCS to  
557 reduce food consumption and subjective appetite following 8 sessions. This suggests that  
558 repeated low-level stimulation may lead to a cumulative improvement in eating-related  
559 measures, however there is not currently sufficient data to confirm this effect. If low-intensity  
560 stimulation is able to modulate eating behaviors across multiple sessions, this may produce  
561 a more consistent effect of tDCS than single-session stimulation but will require greater  
562 resources and commitment from potential participants. Multi-session designs should not  
563 come at the cost of appropriate stimulation parameters, and studies using single-session  
564 stimulation are still important for determining effective parameter ranges and the modulatory  
565 effect of tDCS on measures of eating behavior; they have also demonstrated significant  
566 effects on a number of occasions (6, 7, 28, 45).

567

568 Reflecting on our RoB assessment, the implementation and maintenance of participant and  
569 researcher blinding is the main source of bias across many of the reviewed studies. In  
570 particular, little detail is given around researcher blinding protocols in several studies. It is

571 likely that poor researcher blinding contributes to poor participant blinding, as ineffective  
572 researcher blinding can lead to several confounding factors such as expectation effects,  
573 protocol adjustments or biases in the analysis and reporting of data (91). Researcher  
574 blinding can be achieved through the use of pin-protected devices where the stimulation  
575 parameters are pre-set by an independent individual (e.g., (70)). To control for potential  
576 unblinding of researchers it is recommended that the efficacy of researcher blinding is  
577 measured.

578

579 Additionally, the greater prevalence of adverse events following active tDCS may reduce the  
580 ability to blind participants (92). However, this is of particular debate as not all studies find a  
581 difference in adverse events between active and sham conditions (68). Poor blinding may be  
582 driven by visual cues such as erythema (skin redness), which is more common following  
583 active stimulation (64). This visual discrepancy between active and sham protocols easily  
584 signifies to the participant and researcher that a difference between conditions exists and  
585 potentially which condition the participant has received (64, 93). Six studies report either  
586 greater erythema following active conditions or similar redness following active and sham  
587 protocols (10, 24, 25, 40, 60, 70). Three of these studies reported successful participant  
588 blinding, while also reporting no difference in skin redness (10, 25, 70), which suggests  
589 erythema may indeed be contributing to ineffective participant blinding (64, 93).

590

591 Participant blinding can be maintained by preventing the participant from observing their skin  
592 following stimulation. However, researcher blinding is less straight forward to uphold where  
593 visible differences are evident and this may account for some of the variation in data (94).  
594 Careful consideration of stimulation parameters and device set-up should be made to  
595 minimize the likelihood of erythema and maintain a double-blind design. Additionally, pre-  
596 treatment of the skin with dermatological products may reduce occurrence and severity of  
597 redness, but this may not be appropriate for all studies or participant groups (95). The impact

598 on current resistance by preparing the skin with these products is not well established, and  
599 to account for any potential effects all preparatory steps must be recorded (11).

600

601 The information provided to participants should also be carefully controlled. Providing  
602 information to participants that will lead to an expectation of effect will likely change scores,  
603 resulting in an effect that is unrelated to the stimulation technique (30). Participants should  
604 be given sufficient information to provide informed consent, but this should omit any study  
605 hypotheses or expected effects of the study protocol. Answers provided to any participant  
606 queries or comments made around the efficacy of tDCS should also be controlled. It should  
607 be noted that individuals who have previously undergone or are knowledgeable of tDCS  
608 procedures may be more likely to identify active protocols than tDCS-naïve individuals, and  
609 so the inclusion of those who have previously undergone stimulation should be avoided to  
610 maintain blinding efficacy (96).

611

612 Additional data are required to confirm some of the assumptions we have made, such as the  
613 effective current density range, with further data required to determine the efficacy of some  
614 parameters. We do not expect that all future studies will adhere to the parameters described  
615 in this section, and it is important that further studies test the efficacy of parameters outside  
616 these ranges. However, from the data included in this review, these appear to be the most  
617 effective parameters for modulating eating-related outcomes. Whilst we acknowledge that  
618 the present review does not extend to the discussion of physiological implications of differing  
619 stimulation parameters, we have been able to describe those parameters that appear  
620 effective on a behavioral level. The paucity of research describing the physiological effects of  
621 tDCS remains problematic, ensuring it was not possible to fully discuss these implications in  
622 this review. We encourage researchers to explore the physiological effects of differing tDCS  
623 parameters to highlight the underpinning physiological mechanisms that drive the behavioral  
624 effects we describe here.

625

## 626 **5. CONCLUSION**

627 The first study measuring the effects of tDCS on food craving and consumption was  
628 published more than a decade ago, and we are still at a relatively early stage in our  
629 understanding of the effects and potential role of this technique for the control of eating  
630 behavior. Interest in this area has proliferated over recent years, but many studies have  
631 employed varying study designs and stimulation parameters which makes it difficult to  
632 identify a consistent effect of tDCS. Careful consideration of stimulation parameters is  
633 important for all studies. This is not a new concept with many recent reviews highlighting the  
634 need for consistent and appropriate parameter use (3, 12, 14).

635

636 In this review, we have extended the discussion to incorporate a more comprehensive range  
637 of parameters and have outlined potentially effective ranges for these parameters. We  
638 acknowledge that some of the analyses, conclusions and assumptions we have made are  
639 based on a limited number of studies, which reflects the relative novelty of these studies.  
640 However, there is good evidence to support these conclusions from wider research, some of  
641 which we have included in this review. Initial variation in applied parameters is important for  
642 identifying the most appropriate parameters to apply. However, more consistency in  
643 parameter application is required in future work in order to fully understand the impact of  
644 tDCS and the efficacy of this technique to modulate the hedonic responses to food. This also  
645 highlights the need for publication of null effects and the use of Bayesian statistics, which  
646 can be used to identify those parameters, populations or measures that appear to be outside  
647 the modulatory influence of tDCS. The aim of this review was to identify effective parameter  
648 ranges, and through our discussion we hope to improve the quality of future studies through  
649 the application of appropriate study design and effective stimulation parameters. We also  
650 hope this will also lead to continued discussion around these considerations.

651

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656

#### 657 **AUTHOR CONTRIBUTIONS**

658 **Jordan D. Beaumont:** Conceptualization, Methodology, Validation, Investigation, Data  
659 curation, Writing – original draft, Writing – review & editing, Visualization, Project  
660 administration. **David Starr:** Validation, Data curation. **Natalie C. Smith:** Validation, Data  
661 curation. **Danielle Davis:** Conceptualization, Writing – review & editing, Supervision.  
662 **Michelle Dalton:** Conceptualization, Writing – review & editing, Supervision. **Alexander**  
663 **Nowicky:** Writing – review & editing. **Mark Russell:** Writing – review & editing. **Martin J.**  
664 **Barwood:** Conceptualization, Methodology, Validation, Writing – review & editing,  
665 Supervision.

666

667 **REFERENCES**

- 668 1. Nitsche MA, Paulus W. Sustained excitability elevations induced by transcranial DC  
669 motor cortex stimulation in humans. *Neurology*. 2001;57:1899.
- 670 2. Nitsche MA, Paulus W. Excitability changes induced in the human motor cortex by  
671 weak transcranial direct current stimulation. *The Journal of Physiology*. 2000;527:633-9.
- 672 3. Filmer HL, Dux PE, Mattingley JB. Applications of transcranial direct current  
673 stimulation for understanding brain function. *Trends in Neurosciences*. 2014;37:742-53.
- 674 4. Jamil A, Nitsche MA. What Effect Does tDCS Have on the Brain? *Basic Physiology of*  
675 *tDCS*. *Current Behavioral Neuroscience Reports*. 2017;4:331-40.
- 676 5. Alonso-Alonso M. Translating tDCS into the field of obesity: mechanism-driven  
677 approaches. *Frontiers in Human Neuroscience*. 2013;7:512.
- 678 6. Fregni F, Orsati F, Pedrosa W, Fecteau S, Tome FAM, Nitsche MA, Mecca T,  
679 Macedo EC, Pascual-Leone A, Boggio PS. Transcranial direct current stimulation of the  
680 prefrontal cortex modulates the desire for specific foods. *Appetite*. 2008;51:34-41.
- 681 7. Goldman RL, Borckardt JJ, Frohman HA, O'Neil PM, Madan A, Campbell LK, Budak  
682 A, George MS. Prefrontal cortex transcranial direct current stimulation (tDCS) temporarily  
683 reduces food cravings and increases the self-reported ability to resist food in adults with  
684 frequent food craving. *Appetite*. 2011;56:741-6.
- 685 8. Sedgmond J, Lawrence Natalia S, Verbruggen F, Morrison S, Chambers Christopher  
686 D, Adams Rachel C. Prefrontal brain stimulation during food-related inhibition training:  
687 effects on food craving, food consumption and inhibitory control. *Royal Society Open*  
688 *Science*. 2019;6:181186.
- 689 9. Georgii C, Goldhofer P, Meule A, Richard A, Blechert J. Food craving, food choice  
690 and consumption: The role of impulsivity and sham-controlled tDCS stimulation of the right  
691 dIPFC. *Physiology & Behavior*. 2017;177:20-6.
- 692 10. Gluck ME, Alonso-Alonso M, Piaggi P, Weise CM, Jumpertz-von Schwartzberg R,  
693 Reinhardt M, Wassermann EM, Venti CA, Votruba SB, Krakoff J. Neuromodulation targeted  
694 to the prefrontal cortex induces changes in energy intake and weight loss in obesity. *Obesity*.  
695 2015;23:2149-56.
- 696 11. Antal A, Alekseichuk I, Bikson M, Brockmüller J, Brunoni AR, Chen R, Cohen LG,  
697 Douthwaite G, Ellrich J, Flöel A, Fregni F, George MS, Hamilton R, Hauelsen J, Herrmann  
698 CS, Hummel FC, Lefaucheur JP, Liebetanz D, Loo CK, McCaig CD, Miniussi C, Miranda PC,  
699 Moliadze V, Nitsche MA, Nowak R, Padberg F, Pascual-Leone A, Poppendieck W, Priori A,  
700 Rossi S, Rossini PM, Rothwell J, Rueger MA, Ruffini G, Schellhorn K, Siebner HR, Ugawa  
701 Y, Wexler A, Ziemann U, Hallett M, Paulus W. Low intensity transcranial electric stimulation:  
702 Safety, ethical, legal regulatory and application guidelines. *Clinical Neurophysiology*.  
703 2017;128:1774-809.

- 704 12. Tremblay S, Lepage J-F, Latulipe-Loiselle A, Fregni F, Pascual-Leone A, Théoret H.  
705 The Uncertain Outcome of Prefrontal tDCS. *Brain Stimulation*. 2014;7:773-83.
- 706 13. Fertonani A, Miniussi C. Transcranial Electrical Stimulation: What We Know and Do  
707 Not Know About Mechanisms. *The Neuroscientist*. 2016;23:109-23.
- 708 14. Thair H, Holloway AL, Newport R, Smith AD. Transcranial Direct Current Stimulation  
709 (tDCS): A Beginner's Guide for Design and Implementation. *Frontiers in Neuroscience*.  
710 2017;11:641.
- 711 15. Krause B, Kadosh RC. Not all brains are created equal: the relevance of individual  
712 differences in responsiveness to transcranial electrical stimulation. *Frontiers in Systems*  
713 *Neuroscience*. 2014;8:25.
- 714 16. Hall PA, Vincent CM, Burhan AM. Non-invasive brain stimulation for food cravings,  
715 consumption, and disorders of eating: A review of methods, findings and controversies.  
716 *Appetite*. 2018;124:78-88.
- 717 17. Mostafavi S-A, Khaleghi A, Mohammadi MR, Akhondzadeh S. Is transcranial direct  
718 current stimulation an effective modality in reducing food craving? A systematic review and  
719 meta-analysis. *Nutritional Neuroscience*. 2018:1-13.
- 720 18. Moher D, Liberati A, Tetzlaff J, Altman DG, The PG. Preferred Reporting Items for  
721 Systematic Reviews and Meta-Analyses: The PRISMA Statement. *PLOS Medicine*.  
722 2009;6:e1000097.
- 723 19. Priori A, Berardelli A, Rona S, Accornero N, Manfredi M. Polarization of the human  
724 motor cortex through the scalp. *NeuroReport*. 1998;9.
- 725 20. Higgins JPT, Thomas J, Chandler J, Cumpston M, Li T, Page MJ, Welch VA.  
726 *Cochrane Handbook for Systematic Reviews of Interventions*. Version 6.1 ed: Cochrane;  
727 2020.
- 728 21. Sterne JAC, Savović J, Page MJ, Elbers RG, Blencowe NS, Boutron I, Cates CJ,  
729 Cheng H-Y, Corbett MS, Eldridge SM, Emberson JR, Hernán MA, Hopewell S, Hróbjartsson  
730 A, Junqueira DR, Jüni P, Kirkham JJ, Lasserson T, Li T, McAleenan A, Reeves BC,  
731 Shepperd S, Shrier I, Stewart LA, Tilling K, White IR, Whiting PF, Higgins JPT. RoB 2: a  
732 revised tool for assessing risk of bias in randomised trials. *BMJ*. 2019;366:l4898.
- 733 22. Rohatgi A. WebPlotDigitizer. 2020 [11 March 2021]; 4.4:[Available from:  
734 <https://automeris.io/WebPlotDigitizer>].
- 735 23. Lipsey MW, Wilson DB. *Practical Meta-Analysis*: SAGE Publications; 2000.
- 736 24. Amo Usanos C, Valenzuela PL, de la Villa P, Navarro SM, Melo Aroeira AEd, Amo  
737 Usanos I, Martínez Cancio L, Cuesta Villa L, Shah H, Magerowski G, Alonso-Alonso M.  
738 Neuromodulation of the prefrontal cortex facilitates diet-induced weight loss in midlife  
739 women: a randomized, proof-of-concept clinical trial. *International Journal of Obesity*.  
740 2020;44:568-78.

- 741 25. Heinitz S, Reinhardt M, Piaggi P, Weise CM, Diaz E, Stinson EJ, Venti C, Votruba  
742 SB, Wassermann EM, Alonso-Alonso M, Krakoff J, Gluck ME. Neuromodulation directed at  
743 the prefrontal cortex of subjects with obesity reduces snack food intake and hunger in a  
744 randomized trial. *The American Journal of Clinical Nutrition*. 2017;106:1347-57.
- 745 26. Fassini PG, Das SK, Magerowski G, Marchini JS, da Silva Junior WA, da Silva IR, de  
746 Souza Ribeiro Salgueiro R, Machado CD, Suen VMM, Alonso-Alonso M. Noninvasive  
747 neuromodulation of the prefrontal cortex in young women with obesity: a randomized clinical  
748 trial. *International journal of obesity (2005)*. 2020;44:1279-90.
- 749 27. Fassini PG, Das SK, Suen VMM, Magerowski G, Marchini JS, da Silva Junior WA,  
750 Changyu S, Alonso-Alonso M. Appetite effects of prefrontal stimulation depend on COMT  
751 Val158Met polymorphism: A randomized clinical trial. *Appetite*. 2019;140:142-50.
- 752 28. Montenegro RA, Okano AH, Cunha FA, Gurgel JL, Fontes EB, Farinatti PTV.  
753 Prefrontal cortex transcranial direct current stimulation associated with aerobic exercise  
754 change aspects of appetite sensation in overweight adults. *Appetite*. 2012;58:333-8.
- 755 29. Ljubisavljevic M, Maxood K, Bjekic J, Oommen J, Nagelkerke N. Long-Term Effects  
756 of Repeated Prefrontal Cortex Transcranial Direct Current Stimulation (tDCS) on Food  
757 Craving in Normal and Overweight Young Adults. *Brain Stimulation*. 2016;9:826-33.
- 758 30. Ray MK, Sylvester MD, Helton A, Pittman BR, Wagstaff LE, McRae TR, Turan B,  
759 Fontaine KR, Amthor FR, Boggiano MM. The effect of expectation on transcranial direct  
760 current stimulation (tDCS) to suppress food craving and eating in individuals with overweight  
761 and obesity. *Appetite*. 2019;136:1-7.
- 762 31. Borenstein M, Hedges LV, Higgins JPT, Rothstein HR. *Introduction to Meta-Analysis*:  
763 Wiley; 2021.
- 764 32. Hall PA, Lowe CJ. Cravings, currents and cadavers: What is the magnitude of tDCS  
765 effects on food craving outcomes? *Nutritional Neuroscience*. 2018:1-4.
- 766 33. Van den Noortgate W, López-López JA, Marín-Martínez F, Sánchez-Meca J. Three-  
767 level meta-analysis of dependent effect sizes. *Behavior Research Methods*. 2013;45:576-94.
- 768 34. Van den Noortgate W, López-López JA, Marín-Martínez F, Sánchez-Meca J. Meta-  
769 analysis of multiple outcomes: a multilevel approach. *Behavior Research Methods*.  
770 2015;47:1274-94.
- 771 35. The R Foundation. *The R Project for Statistical Computing*. 2021; Available from:  
772 <https://www.r-project.org/>.
- 773 36. Schwarzer G, Carpenter JR, Rücker G. *Meta-Analysis with R*: Springer International  
774 Publishing; 2015.
- 775 37. Cohen J. A power primer. *Psychological Bulletin*. 1992;112:155-9.

- 776 38. Deeks JJ, Higgins JPT, Altman DG. Analysing data and undertaking meta-analyses.  
777 In: Higgins JPT, Thomas J, Chandler J, Cumpston M, Li T, Page M, Welch V, editors.  
778 Cochrane Handbook for Systematic Reviews of Interventions: Cochrane Statistical Methods  
779 Group; 2021.
- 780 39. Egger M, Smith GD, Schneider M, Minder C. Bias in meta-analysis detected by a  
781 simple, graphical test. *BMJ*. 1997;315:629.
- 782 40. Bravo GL, Poje AB, Perissinotti I, Marcondes BF, Villamar MF, Manzardo AM, Luque  
783 L, LePage JF, Stafford D, Fregni F, Butler MG. Transcranial direct current stimulation  
784 reduces food-craving and measures of hyperphagia behavior in participants with Prader-Willi  
785 syndrome. *American Journal of Medical Genetics Part B: Neuropsychiatric Genetics*.  
786 2016;171:266-75.
- 787 41. Lapenta OM, Di Sierve K, de Macedo EC, Fregni F, Boggio PS. Transcranial direct  
788 current stimulation modulates ERP-indexed inhibitory control and reduces food consumption.  
789 *Appetite*. 2014;83:42-8.
- 790 42. Kekic M, McClelland J, Campbell I, Nestler S, Rubia K, David AS, Schmidt U. The  
791 effects of prefrontal cortex transcranial direct current stimulation (tDCS) on food craving and  
792 temporal discounting in women with frequent food cravings. *Appetite*. 2014;78:55-62.
- 793 43. Chen S, Jackson T, Dong D, Zhang X, Chen H. Exploring effects of single-session  
794 anodal tDCS over the inferior frontal gyrus on responses to food cues and food cravings  
795 among highly disinhibited restrained eaters: A preliminary study. *Neuroscience Letters*.  
796 2019;706:211-6.
- 797 44. To C, Falcone M, Loughhead J, Logue-Chamberlain E, Hamilton R, Kable J, Lerman  
798 C, Ashare RL. Got chocolate? Bilateral prefrontal cortex stimulation augments chocolate  
799 consumption. *Appetite*. 2018;131:28-35.
- 800 45. Burgess EE, Sylvester MD, Morse KE, Amthor FR, Mrug S, Lokken KL, Osborn MK,  
801 Soleymani T, Boggiano MM. Effects of transcranial direct current stimulation (tDCS) on  
802 binge-eating disorder. *International Journal of Eating Disorders*. 2016;49:930-6.
- 803 46. Max SM, Plewnia C, Zipfel S, Giel KE, Schag K. Combined antisaccade task and  
804 transcranial direct current stimulation to increase response inhibition in binge eating  
805 disorder. *European Archives of Psychiatry and Clinical Neuroscience*. 2020.
- 806 47. Kekic M, McClelland J, Bartholdy S, Boysen E, Musiat P, Dalton B, Tiza M, David  
807 AS, Campbell IC, Schmidt U. Single-Session Transcranial Direct Current Stimulation  
808 Temporarily Improves Symptoms, Mood, and Self-Regulatory Control in Bulimia Nervosa: A  
809 Randomised Controlled Trial. *PloS one*. 2017;12:e0167606.
- 810 48. Mattavelli G, Gallucci A, Schiena G, D'Agostino A, Sasseti T, Bonora S, Bertelli S,  
811 Benetti A, Tugnoli E, Ruggiero GM, Sassaroli S, Lauro LR, Gambini O, Papagno C.  
812 Transcranial direct current stimulation modulates implicit attitudes towards food in eating  
813 disorders. *International Journal of Eating Disorders*. 2019;52:576-81.

- 814 49. Li LM, Uehara K, Hanakawa T. The contribution of interindividual factors to variability  
815 of response in transcranial direct current stimulation studies. *Frontiers in Cellular*  
816 *Neuroscience*. 2015;9:181.
- 817 50. de Graaf TA, Sack AT. When and How to Interpret Null Results in NIBS: A Taxonomy  
818 Based on Prior Expectations and Experimental Design. *Frontiers in Neuroscience*.  
819 [10.3389/fnins.2018.00915]. 2018;12:915.
- 820 51. Dohle S, Diel K, Hofmann W. Executive functions and the self-regulation of eating  
821 behavior: A review. *Appetite*. 2018;124:4-9.
- 822 52. Gluck ME, Viswanath P, Stinson EJ. Obesity, Appetite, and the Prefrontal Cortex.  
823 *Current Obesity Reports*. 2017;6:380-8.
- 824 53. Alonso-Alonso M, Pascual-Leone A. The Right Brain Hypothesis for Obesity. *JAMA*.  
825 2007;297:1819-22.
- 826 54. Carvalho S, Sampaio A, Mendes AJ, Lema A, Vieira D, Goncalves OF, Leite J.  
827 Polarity specific effects of cross-hemispheric tDCS coupled with approach-avoidance  
828 training on chocolate craving. *Frontiers in Pharmacology*. [Article]. 2019;9.
- 829 55. Marron EM, Viejo-Sobera R, Cuatrecasas G, Redolar-Ripoll D, Lorda PG, Datta A,  
830 Bikson M, Magerowski G, Alonso-Alonso M. Prefronto-cerebellar neuromodulation affects  
831 appetite in obesity. *International Journal of Obesity*. 2019;43:2119-24.
- 832 56. Beaumont JD, Smith NC, Starr D, Davis D, Dalton M, Nowicky A, Russell M,  
833 Barwood MJ. Modulating eating behavior with transcranial direct current stimulation (tDCS):  
834 A systematic literature review on the impact of eating behavior traits. *Obesity Reviews*.  
835 [<https://doi.org/10.1111/obr.13364>]. 2021.
- 836 57. Vicario CM, Salehinejad MA, Mosayebi-Samani M, Maezawa H, Avenanti A, Nitsche  
837 MA. Transcranial direct current stimulation over the tongue motor cortex reduces appetite in  
838 healthy humans. *Brain Stimulation*. 2020;13:1121-3.
- 839 58. Bikson M, Datta A, Rahman A, Scaturro J. Electrode montages for tDCS and weak  
840 transcranial electrical stimulation: Role of "return" electrode's position and size. *Clinical*  
841 *Neurophysiology*. 2010;121:1976-8.
- 842 59. Batsikadze G, Rezaee Z, Chang D-I, Gerwig M, Herlitze S, Dutta A, Nitsche MA,  
843 Timmann D. Effects of cerebellar transcranial direct current stimulation on cerebellar-brain  
844 inhibition in humans: A systematic evaluation. *Brain Stimulation: Basic, Translational, and*  
845 *Clinical Research in Neuromodulation*. 2019;12:1177-86.
- 846 60. Jauch-Chara K, Kistenmacher A, Herzog N, Schwarz M, Schweiger U, Oltmanns KM.  
847 Repetitive electric brain stimulation reduces food intake in humans. *The American Journal of*  
848 *Clinical Nutrition*. 2014;100:1003-9.
- 849 61. Imburgio MJ, Orr JM. Effects of prefrontal tDCS on executive function:  
850 Methodological considerations revealed by meta-analysis. *Neuropsychologia*. 2018;117:156-  
851 66.

- 852 62. Lowe CJ, Vincent C, Hall PA. Effects of Noninvasive Brain Stimulation on Food  
853 Cravings and Consumption: A Meta-Analytic Review. *Psychosomatic Medicine*. 2017;79.
- 854 63. Nitsche MA, Paulus W. Transcranial direct current stimulation – update 2011.  
855 *Restorative Neurology and Neuroscience*. 2011;29:463-92.
- 856 64. O’Connell NE, Cossar J, Marston L, Wand BM, Bunce D, Moseley GL, De Souza LH.  
857 Rethinking Clinical Trials of Transcranial Direct Current Stimulation: Participant and  
858 Assessor Blinding Is Inadequate at Intensities of 2mA. *PLOS ONE*. 2012;7:e47514.
- 859 65. Monte-Silva K, Kuo M-F, Hessenthaler S, Fresnoza S, Liebetanz D, Paulus W,  
860 Nitsche MA. Induction of Late LTP-Like Plasticity in the Human Motor Cortex by Repeated  
861 Non-Invasive Brain Stimulation. *Brain Stimulation*. 2013;6:424-32.
- 862 66. Hassanzahraee M, Nitsche MA, Zoghi M, Jaberzadeh S. Determination of anodal  
863 tDCS duration threshold for reversal of corticospinal excitability: An investigation for  
864 induction of counter-regulatory mechanisms. *Brain Stimulation*. 2020;13:832-9.
- 865 67. Gandiga PC, Hummel FC, Cohen LG. Transcranial DC stimulation (tDCS): A tool for  
866 double-blind sham-controlled clinical studies in brain stimulation. *Clinical Neurophysiology*.  
867 2006;117:845-50.
- 868 68. Brunoni AR, Amadera J, Berbel B, Volz MS, Rizzerio BG, Fregni F. A systematic  
869 review on reporting and assessment of adverse effects associated with transcranial direct  
870 current stimulation. *International Journal of Neuropsychopharmacology*. 2011;14:1133-45.
- 871 69. Nikolin S, Huggins C, Martin D, Alonzo A, Loo CK. Safety of repeated sessions of  
872 transcranial direct current stimulation: A systematic review. *Brain Stimulation*. 2018;11:278-  
873 88.
- 874 70. Beaumont JD, Davis D, Dalton M, Nowicky A, Russell M, Barwood MJ. The effect of  
875 transcranial direct current stimulation (tDCS) on food craving, reward and appetite in a  
876 healthy population. *Appetite*. 2021;157:105004.
- 877 71. Fassi L, Cohen Kadosh R. Letter to the editor: How some brain stimulation studies  
878 fail to evaluate blinding adequately. *Journal of Psychiatric Research*. 2021;137:452-3.
- 879 72. Fassi L, Kadosh RC. Is it all in our head? When subjective beliefs about receiving an  
880 intervention are better predictors of experimental results than the intervention itself. *bioRxiv*.  
881 2020:2020.12.06.411850.
- 882 73. Grundeis F, Brand C, Kumar S, Rullmann M, Mehnert J, Pleger B. Non-invasive  
883 Prefrontal/Frontal Brain Stimulation Is Not Effective in Modulating Food Reappraisal Abilities  
884 or Calorie Consumption in Obese Females. *Frontiers in Neuroscience*. 2017;11:334.
- 885 74. Dedoncker J, Brunoni AR, Baeken C, Vanderhasselt M-A. A Systematic Review and  
886 Meta-Analysis of the Effects of Transcranial Direct Current Stimulation (tDCS) Over the  
887 Dorsolateral Prefrontal Cortex in Healthy and Neuropsychiatric Samples: Influence of  
888 Stimulation Parameters. *Brain Stimulation*. 2016;9:501-17.

- 889 75. McCreery DB, Agnew WF, Yuen TGH, Bullara L. Charge density and charge per  
890 phase as cofactors in neural injury induced by electrical stimulation. *IEEE Transactions on*  
891 *Biomedical Engineering*. 1990;37:996-1001.
- 892 76. Nitsche MA, Liebetanz D, Lang N, Antal A, Tergau F, Paulus W. Safety criteria for  
893 transcranial direct current stimulation (tDCS) in humans. *Clinical Neurophysiology*.  
894 2003;114:2220-2.
- 895 77. Noetscher GM, Yanamadala J, Makarov SN, Pascual-Leone A. Comparison of  
896 Cephalic and Extracerebral Montages for Transcranial Direct Current Stimulation—A  
897 Numerical Study. *IEEE Transactions on Biomedical Engineering*. 2014;61:2488-98.
- 898 78. Im C-H, Park J-H, Shim M, Chang WH, Kim Y-H. Evaluation of local electric fields  
899 generated by transcranial direct current stimulation with an extracerebral reference electrode  
900 based on realistic 3D body modeling. *Physics in Medicine and Biology*. 2012;57:2137-50.
- 901 79. Miranda PC, Lomarev M, Hallett M. Modeling the current distribution during  
902 transcranial direct current stimulation. *Clinical Neurophysiology*. 2006;117:1623-9.
- 903 80. Pleger B. Invasive and Non-invasive Stimulation of the Obese Human Brain.  
904 *Frontiers in Neuroscience*. 2018;12:884.
- 905 81. Moliadze V, Antal A, Paulus W. Electrode-distance dependent after-effects of  
906 transcranial direct and random noise stimulation with extracerebral reference electrodes.  
907 *Clinical Neurophysiology*. 2010;121:2165-71.
- 908 82. Nitsche MA, Doemkes S, Karaköse T, Antal A, Liebetanz D, Lang N, Tergau F,  
909 Paulus W. Shaping the Effects of Transcranial Direct Current Stimulation of the Human  
910 Motor Cortex. *Journal of Neurophysiology*. 2007;97:3109-17.
- 911 83. Leite J, Gonçalves ÓF, Pereira P, Khadka N, Bikson M, Fregni F, Carvalho S. The  
912 differential effects of unihemispheric and bihemispheric tDCS over the inferior frontal gyrus  
913 on proactive control. *Neuroscience Research*. 2018;130:39-46.
- 914 84. Rush S, Driscoll DA. Current Distribution in the Brain From Surface Electrodes.  
915 *Anesthesia & Analgesia*. 1968;47.
- 916 85. Miniussi C, Harris JA, Ruzzoli M. Modelling non-invasive brain stimulation in  
917 cognitive neuroscience. *Neuroscience & Biobehavioral Reviews*. 2013;37:1702-12.
- 918 86. Sun W, Kober H. Regulating food craving: From mechanisms to interventions.  
919 *Physiology & Behavior*. 2020;222:112878.
- 920 87. Hill AT, Fitzgerald PB, Hoy KE. Effects of Anodal Transcranial Direct Current  
921 Stimulation on Working Memory: A Systematic Review and Meta-Analysis of Findings From  
922 Healthy and Neuropsychiatric Populations. *Brain Stimulation*. 2016;9:197-208.



- 923 88. Martin DM, Liu R, Alonzo A, Green M, Loo CK. Use of transcranial direct current  
924 stimulation (tDCS) to enhance cognitive training: effect of timing of stimulation. *Experimental*  
925 *Brain Research*. 2014;232:3345-51.
- 926 89. Gill J, Shah-Basak PP, Hamilton R. It's the Thought That Counts: Examining the  
927 Task-dependent Effects of Transcranial Direct Current Stimulation on Executive Function.  
928 *Brain Stimulation*. 2015;8:253-9.
- 929 90. Alonzo A, Brassil J, Taylor JL, Martin D, Loo CK. Daily transcranial direct current  
930 stimulation (tDCS) leads to greater increases in cortical excitability than second daily  
931 transcranial direct current stimulation. *Brain Stimulation*. 2012;5:208-13.
- 932 91. Horvath J, Carter O, Forte J. Transcranial direct current stimulation: five important  
933 issues we aren't discussing (but probably should be). *Frontiers in Systems Neuroscience*.  
934 2014;8:2.
- 935 92. Kessler SK, Turkeltaub PE, Benson JG, Hamilton RH. Differences in the experience  
936 of active and sham transcranial direct current stimulation. *Brain Stimulation*. 2012;5:155-62.
- 937 93. Palm U, Reisinger E, Keeser D, Kuo M-F, Pogarell O, Leicht G, Mulert C, Nitsche  
938 MA, Padberg F. Evaluation of Sham Transcranial Direct Current Stimulation for  
939 Randomized, Placebo-Controlled Clinical Trials. *Brain Stimulation: Basic, Translational, and*  
940 *Clinical Research in Neuromodulation*. 2013;6:690-5.
- 941 94. Horvath JC. Are current blinding methods for transcranial direct current stimulation  
942 (tDCS) effective in healthy populations? *Clinical Neurophysiology*. 2015;126:2045-6.
- 943 95. Guarienti F, Caumo W, Shiozawa P, Cordeiro Q, Boggio PS, Benseñor IM, Lotufo  
944 PA, Bikson M, Brunoni AR. Reducing Transcranial Direct Current Stimulation-Induced  
945 Erythema With Skin Pretreatment: Considerations for Sham-Controlled Clinical Trials.  
946 *Neuromodulation: Technology at the Neural Interface*. [<https://doi.org/10.1111/ner.12230>].  
947 2015;18:261-5.
- 948 96. Ambrus GG, Al-Moyed H, Chaieb L, Sarp L, Antal A, Paulus W. The fade-in – Short  
949 stimulation – Fade out approach to sham tDCS – Reliable at 1 mA for naïve and  
950 experienced subjects, but not investigators. *Brain Stimulation*. 2012;5:499-504.
- 951 97. Klem GH, Lüders HO, Jasper HH, Elger C. The ten-twenty electrode system of the  
952 International Federation. *The International Federation of Clinical Neurophysiology*.  
953 *Electroencephalography and clinical neurophysiology Supplement*. 1999;52:3-6.
- 954 98. Ray MK, Sylvester MD, Osborn L, Helms J, Turan B, Burgess EE, Boggiano MM.  
955 The critical role of cognitive-based trait differences in transcranial direct current stimulation  
956 (tDCS) suppression of food craving and eating in frank obesity. *Appetite*. 2017;116:568-74.  
957

958 **FIGURE CAPTIONS**

959

960

961 **Figure 1** A comparison of cephalic montages; black circles represent target (left) or  
962 reference (right) electrode locations. Image adapted from Klem, Lüders (97).

963

964 **Figure 2** A comparison between active and commonly applied sham protocols. In active  
965 tDCS, the current is ramped up to the desired intensity and delivered for several minutes  
966 before being ramped down and switched off. Sham protocols involve the current being  
967 ramped up to the desired intensity and then either immediately ramped down and turned off  
968 (Sham A), or delivered for several seconds before being ramped down (Sham B).

969 Alternatively, one of these sham protocols is repeated at the end of the stimulation period to  
970 imitate both incremental and decremental currents integral to active tDCS protocols (Sham  
971 C).

972

973 **Figure 3** Forest plots comparing single- and multi-session protocol across (a) food craving  
974 and (b) food consumption measures.

975

976 **Figure 4** Summary of variation in tDCS parameters observed across the reviewed studies.

977

978 **Table 1** Literature search terms

Database	Search Terms
MEDLINE PsycINFO Scopus	<i>("noninvasive brain stimulation" OR "non-invasive brain stimulation" OR "transcranial direct current stimulation" OR "transcranial current stimulation" OR tDCS) AND (appetit* OR food OR "food crav*" OR "food reward" OR "food preference*" OR "food cue" OR "food consumption" OR eat* OR calorie* OR "calorie intake" OR "calorie consumption" OR energy OR "energy intake" OR "energy consumption" OR bing* OR "binge eat*" OR snack*)</i>
Science Direct	<i>("transcranial direct current stimulation" OR tDCS) AND ("food craving" OR "food reward" OR "food preference" OR "food consumption")</i>

979

980 **Table 2** Comparison of tDCS parameters across studies

	Intervention	Montage <sup>a,b</sup>			Current Intensity (mA)	Stimulation Duration			Number of Stimulation Sessions
		Target Electrode	Reference Electrode	Electrode Size (cm <sup>2</sup> )		Ramp (seconds)	Active (minutes)	Sham (seconds)	
Amo Usanos et al. (2020) (24)	Anodal, Sham	F3	Right supraorbital	25	2.0	30	20	15 at start and end	8
Beaumont et al. (2021) (70)	Anodal, Sham	F4	Oz	25 / 51 <sup>c</sup>	2.0	30	20	36	1
Bravo et al. (2016) (40)	Anodal, Sham	F4	Left supraorbital	35	2.0	15	30	0 (ramp only)	5
Burgess et al. (2016) (45)	Anodal, Sham	F4	F3	Not reported	2.0	Not reported	20	120 at start, 60 at end	1
Carvalho et al. (2019) (54)	Anodal, Cathodal, Sham	F4	F3	35	2.0	15	20	15	1
Chen et al. (2019) (43)	Anodal, Sham	Right IFG (midpoint F4-F8)	Left cheek	25	1.5	30	20	0 (ramp only)	1
Fassini et al. (2019) (27)	Anodal, Sham	F3	Right supraorbital	25	2.0	30	30	30	16
Fassini et al. (2020) (26)	Anodal, Sham	F3	Right supraorbital	25	2.0	30	30	30	16

(Table 2 continued)

Fregni et al. (2008) (6)	Anodal, Cathodal, Sham	F3 / F4	F4 / F3	35	2.0	Not reported	20	30	1
Georgii et al. (2017) (9)	Anodal, Sham	F4	F3	35	1.0	15	20	15	1
Gluck et al. (2015) (10)	Anodal, Cathodal, Sham	F3	Left forearm / Right supraorbital	25	2.0	30	40	15	3
Goldman et al. (2011) (7)	Anodal, Sham	F4	F3	Not reported	2.0	30	20	60	1
Grundeis et al. (2017) (73)	Anodal, Cathodal, Sham	F8	Af7	35	2.0	30	20	0 (ramp only)	1
Heinitz et al. (2017) (25)	Anodal, Sham	F3	Right supraorbital	35	2.0	Not reported	40	10	15
Jauch-Chara et al. (2014) (60)	Anodal, Sham	Right DLPFC	Left supraorbital	35	1.0	8	20	0 (ramp only)	8
Kekic et al. (2014) (42)	Anodal, Sham	F4	F3	25	2.0	10	20	30	1
Kekic et al. (2017) (47)	Anodal, Cathodal, Sham	F4	F3	25	2.0	10	20	30	1

(Table 2 continued)

Lapenta et al. (2014) (41)	Anodal, Sham	F4	F3	35	2.0	15	20	30	1
Ljubisavljevic et al. (2016) (29)	Anodal, Sham	F4	Left forearm	35	2.0	30	20	0 (ramp only)	5
Marron et al. (2019) (55)	Anodal, Sham	F3	Right cerebellum	25	2.0	Not reported	20	Not reported	1
Mattavelli et al. (2019) (48)	Anodal, Sham	Midpoint Fz-F3 / O2-PO8	Contralateral supraorbital	16 / 35 °	1.0	10	20	40 at start, 30 at end	1
Max et al. (2020) (46)	Anodal, Sham	F4	Left deltoid muscle	35	1.0 / 2.0	5	20	46	1
Montenegro et al. (2012) (28)	Anodal, Sham	F3	Fp2	35	2.0	Not reported	20	30	1
Ray et al. (2017) (98)	Anodal, Sham	F4	F3	24	2.0	Not reported	20	Not reported	Not reported
Ray et al. (2019) (30)	Anodal, Sham	F4	F3	24	2.0	Not reported	20	60 at start and end	Not reported
Sedgmond et al. (2019) (8)	Anodal, Sham	F4	F3	35	2.0	10	20	30	1
To et al. (2018) (44)	Anodal, Sham	Right IFG (midpoint F4-F8)	Midpoint F3-F7	25	2.0	30	20	0 (ramp only)	Not reported

(Table 2 continued)

Vicario et al. (2020) (57)	Anodal, Cathodal, Sham	Left tnM1	Right mastoid process	35	1.0	30	15	0 (ramp only)	1
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*Af7, anterior frontal area 7; DLPFC, dorsolateral prefrontal cortex; F3, frontal area 3; F4, frontal area 4; F7, frontal area 7; F8, frontal area 8; Fp2, fronto-polar area 2; Fz, frontal zero point; IFG, inferior frontal gyrus; mA, milliampere; O2, occipital area 2; Oz, occipital zero point; PO2, parieto-occipital area 2; tnM1, area of primary motor cortex representing the tongue muscle*

<sup>a</sup> See Klem et al. (1999) (97).

<sup>b</sup> All sham protocols used the same montage as active protocols.

<sup>c</sup> Target electrode size / reference electrode size

982 **Table 3** Proposed Effective tDCS Parameters

Montage	Target: Right DLPFC Reference: Cortical region away from DLPFC, or extracephalic region
Electrode Size	Target: $\leq 35 \text{ cm}^2$ Reference: Equal or greater than target electrode
Current Intensity	1.5 – 2.0 mA
Current Density	0.057 – 0.080 mA·cm <sup>-2</sup>
Stimulation Duration	20 minutes
Inter-session Interval	Single-session: >48 hours Multi-session: $\leq 24$ hours
Offline / Online Protocol	Offline; Unrelated media used as an online task may be appropriate for standardizing participants' thoughts during stimulation

983



984 **Supplemental Digital Content**

985

986

987 **Table S1** PRISMA checklist.

988

989 **Table S2** Summary of meta-analytic data.

990

991 **Table S3** Output of multi-level modelling.

992

993 **Table S4** Summary of heterogeneity and publication bias data across eating-related  
994 measures.

995

996 **Figure S1** PRISMA flow diagram detailing the search and selection process performed to  
997 identify studies applying tDCS for the modulation of eating behaviors.

998

999 **Figure S2** Overall risk of bias across the 28 reviewed studies.

1000

1001 **Figure S3** Risk of bias assessment within studies.

1002

1003 **Figure S4** Contour-enhanced funnel plots across eating-related measures.

1004

1005 **Figures S5 to S10** Forest plots comparing montages.

1006

1007 **Figures S11 to S16** Forest plots comparing cephalic versus extracephalic montages.

1008

1009 **Figures S17 to S22** Forest plots comparing current intensities.

1010

1011 **Figures S23 to S28** Forest plots comparing current densities.

1012

1013 **Figures S29 to S34** Forest plots comparing blinding success.

1014

1015 **Figures S35 to S40** Forest plots comparing single- versus double-blind protocols.

1016

1017 **Figures S41 to S46** Forest plots comparing online versus offline protocols.

1018