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Can transcranial direct current stimulation (tDCS) improve impulsivity in healthy and psychiatric adult populations? A systematic review

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ABSTRACT

Impulsivity is a multidimensional phenomenon that remains hard to define. It compounds the core pathological construct of many neuropsychiatric illnesses, and despite its close relation to suicide risk, it currently has no specific treatment. Transcranial direct current stimulation (tDCS) is a non-invasive brain stimulation technique whose application results in cognitive function improvement, both in healthy and psychiatric populations. Following PRISMA recommendations, a systematic review of the literature concerning tDCS's effects on impulsive behaviour was performed using the PubMed database. The research was based on the combination of the keyword 'tDCS' with 'impulsivity', 'response inhibition', 'risk-taking', 'planning', 'delay discounting' or 'craving'. The initial search yielded 309 articles, 92 of which were included. Seventy-four papers demonstrated improvement in task performance related to impulsivity in both healthy and clinical adult populations. However, results were often inconsistent. The conditions associated with improvement, such as tDCS parameters and other aspects that may influence tDCS's outcomes, are discussed. The overall effects of tDCS on impulsivity are promising. Yet further research is required to develop a more comprehensive understanding of impulsivity, allowing for a more accurate assessment of its behavioural outcomes as well as a definition of tDCS therapeutic protocols for impulsive disorders.

KEYWORDS

Transcranial direct current stimulation; Impulsivity; Dorsolateral prefrontal cortex; Psychiatric disorders; Healthy subjects

1. INTRODUCTION

Despite its influence on daily actions and despite being mentioned in the diagnostic criteria of several psychiatric disorders, impulsivity is a multidimensional concept that remains hard to define (1–3). It is understood as a personality dimension as well as a component of the initiation of behaviours (4,5) that are usually premature, inappropriate, conceived without forethought or conscious judgment and without regard to their consequences (6,7). According to current perspectives, it involves heightened delay aversion, increased risk-taking, low planning ability and poor focus on relevant stimuli or poor inhibition of irrelevant ones (8).

Impulsivity is as a core pathological construct of psychiatric illnesses such as borderline personality disorder, antisocial personality disorder, attention deficit/hyperactivity disorder (ADHD), and substance use/dependence (1,6,9,10). It is closely related to suicide risk, and individuals who are prone to impulsive behaviour are often afflicted with other conditions, such as risk-seeking, defective harm avoidance or risky sexual behaviour (11–15). These pathological manifestations are associated with a substantial loss of quality of life, leading to personal suffering, family disruption and increased healthcare use.

Different measures have been developed in an attempt to evaluate impulsivity's multidimensional nature (2). Assessment usually includes self-reported measures that rely on self-perceptions of behaviour and/or behavioural tasks divided in two categories: those measuring impulsive decision-making and those that measure impulsive action (16). From a neurobiological perspective, a robust body of literature suggests that impulsivity and deficits in impulse control are associated with abnormalities in neuropsychological, neuro-anatomical and neurotransmitter functions (2,17). Evidence from patients with focal brain lesions and from healthy volunteers using functional magnetic resonance imaging and transcranial stimulation implicated distinct but inter-related neurocircuits including limbic, striatal and

prefrontal structures (18). The prefrontal cortex (PFC) plays a key role in cognitive control, modulating functions such as response inhibition control, selective attention, planning and delay discounting (2,7,19,20). The dorsolateral PFC (dlPFC) is crucial in the neural network of executive functions and cognitive control by providing top-down input for task-appropriate behaviours (21). It has also been widely implicated in processes of cognitive control, especially in adjusting behaviour, during tasks involving response conflict, errors in performance and negative feedback (22–26). The orbitofrontal cortex (OFC) and ventrolateral PFC are thought to play a role in correcting and regulating emotional and behavioural response (27), while the right inferior frontal gyrus (IFG) is implicated in response inhibition (7).

Transcranial direct current stimulation (tDCS) is a non-invasive brain stimulation (NIBS) technique that delivers subthreshold electrical current to the scalp, manipulating the resting membrane potential of the targeted area's cortical neurons (28–30). When the stimulation is applied continually over several minutes (commonly 10 to 20 min), the induced excitability changes may last for up to an hour (31,32). The tDCS technique differs from other NIBS methods by not inducing neuronal action potentials; instead, the tissue is polarised, modifying spontaneous neuronal excitability and activity by a tonic de- or hyperpolarisation of resting membrane potential (30). Neuromodulation by tDCS has been shown to be a painless and safe method with few adverse effects (29,30). The device is small, low cost and can even be distributed for home use (33). Hence, it represents a valuable tool that can be used for different purposes; for instance, as a therapeutic device for neuropsychiatric disorders (33–35). Improvements in cognitive functions have been observed after treating both healthy individuals (28,29) and psychiatric patients with tDCS (34). To date, most studies conducted on healthy individuals have assessed the effect of tDCS in enhancing verbal and visuospatial components of working memory, learning processes and other executive functions (28).

A growing number of studies have sought to directly modulate cortical activation as means of reducing impulsivity. We therefore conducted a systematic review of the scientific literature regarding the efficacy of tDCS on reducing impulsive behaviour in both healthy and psychiatric adult populations. Better understanding of its application may contribute to a more comprehensive definition of impulsivity as well as to standardise therapeutic methods directed towards impulsiveness-related disorders.

2. METHODS

2.1. Search strategy

This systematic review was conducted in accordance with PRISMA guidelines recommendations (36). Two authors (JTM and DB) independently screened the PubMed database until December 2018. The search strategy was based on the combination of the keyword 'tDCS' with each one of the following terms ('tDCS AND'): 'impulsivity', 'response inhibition', 'risk-taking', 'planning', 'delay discounting' or 'craving'. The keywords were chosen in accordance with current perspectives on the multidimensional construct of impulsivity (1,2,4,5,7,8,37). There was no restriction on the date of publication. Following de-duplication, studies were sorted by title and then abstract, with the full text of potentially relevant articles obtained in order to conduct a quality assessment and make a decision regarding their inclusion in the final sample. Furthermore, the references of each included article were screened following the same steps, which allowed for the identification of additional relevant studies. Discrepancies between reviewers were solved through a discussion with two other authors (GC and MN) until consensus was reached.

2.2. Inclusion and exclusion criteria

Studies met the inclusion criteria if they (a) studied an adult population, between 18 and 65 years old; (b) included healthy participants or patients suffering from psychiatric disorders;

(c) were randomised controlled trials (RCTs); (d) included an assessment of tDCS's effects on impulsivity; (e) were published by peer-reviewed journals; and (f) were available in English. Articles that did not meet all the inclusion criteria or met any of the following exclusion criteria were not considered in this review: (a) a non-human population (i.e., animal models); (b) a population younger than 18 years or older than 65 years old; (c) a population suffering from any disease or comorbidity other than psychiatric disorders; (d) used another study design besides RCT (open-label trials, case reports, reviews, meta-analysis, etc.); (e) used NIBS techniques other than tDCS; (f) no assessment of tDCS effects on impulsivity; and (g) not available in English.

3. RESULTS

The initial search yielded 309 articles. Fifty six papers were duplicated and therefore removed. Additionally, 171 papers were excluded based on their populations—specifically, populations including diseases or comorbidities other than psychiatric disorders (n = 4), children and adolescents (n = 8), older adults (n = 5) and non-humans (n = 9)—for not using tDCS (n = 18), for not including an assessment of impulsivity outcomes (n = 76) and for not being RCTs (n = 51). The references of the 82 relevant studies were then screened, and 10 more papers were identified. Hence, 92 articles were included, as illustrated in Figure 1.

Most of the included trials (n = 57) evaluated tDCS's effects on the impulsivity of healthy individuals. Studies concerning clinical populations (n = 35) assessed 12 different disorders: ADHD (n = 2), alcohol dependence (n = 11), binge-eating disorder (n = 1), bulimia nervosa (n = 1), cocaine use (n = 1), crack cocaine use (n = 4), heroin use (n = 1), marijuana use (n = 1), unipolar major depressive disorder (n = 1), methamphetamine use (n = 3) and tobacco dependence (n = 9).

In line with the multidimensional aspect of impulsivity, studies were classified according to the dimension they evaluated. Five dimensions were identified for analysis: response inhibition, risk-taking, planning, delay discounting and craving. When studies applied multiple tasks to measure one or several dimensions, each task was treated as an independent trial.

3.1. Response Inhibition

Forty-four papers evaluated tDCS's impact on response inhibition (Table 1). Thirty-five of them were conducted on healthy volunteers. As two of them applied more than one task to assess response inhibition (38,39), the equivalent of 38 results were considered: 23 showed positive effects with increase on inhibitory control (38–60), while five displayed negative effects (61–65) and ten found no significant effects (38,38,39,66–72). Common targets were the IFG using unilateral and bilateral montages; the dlPFC, unilaterally and bilaterally; and the pre-supplementary motor area (pre-SMA). Less common targets were the right inferior frontal cortex (IFC), the right inferior frontal junction (IFJ), the OFC, the superior medial frontal cortex (sMFC) and the left lateral PFC (lPFC). Current densities ranged from the estimated values of 0.028 to 0.166 mA/cm² and were applied between 4.12 and 30 min in single or multiple (up to 16) sessions. Three results were observed online (i.e., during the stimulation session) (41,54,56).

Notably, Mansouri and colleagues' study (58) obtained improvement on inhibitory performance when stimulation was associated with high-tempo music as background noise rather than no music at all. Jacobson and colleagues (45) demonstrated the higher efficacy of unilateral anode stimulation effects over the right IFG when compared to a bilateral montage. Furthermore, Ditye and co-workers (46) observed a cumulative effect with improvement on stop-signal task (SST) performance after the third and fourth days of stimulation over the right IFG. Hogeveen and colleagues (43) found a statistically similar increase in response

inhibition when comparing high-definition (HD)-tDCS and conventional tDCS over the IFC. Nieratschker and co-workers (62) reported interactions between the catechol-O-methyltransferase (COMT) genotype and stimulation condition. They observed a response inhibition impairment under cathodal stimulation of the left dlPFC in Val/Val homozygotes. Weidacker and colleagues (72) observed that inhibitory performance improved after cathodal stimulation over the right dlPFC in subjects who had higher cold-heartedness scores on the Psychopathic Personality Inventory.

In addition, nine papers assessed tDCS's impact on response inhibition of clinical populations: five reported positive effects (73–77), while four observed no significant effects (78–81). Participants were diagnosed with ADHD (78,79), unipolar major depression (74), alcohol dependence (73,75,80), methamphetamine use (76), tobacco dependence (81) and gambling disorder (77). Only the dlPFC in unilateral and bilateral montages was targeted. The current densities varied between 0.028 and 0.08 mA/cm², and stimulation was applied during single or multiple (up to 10) sessions lasting from 10–26 min. Nakamura-Palacios and colleagues (73) had a population of 49 alcohol dependents, Lesch's types I to IV, and significant improvement was only obtained on Lesch's type IV patients after anodal stimulation to the left dlPFC.

3.2. Risk-taking

Eighteen studies assessed tDCS's effects on risk-taking (Table 2). Healthy participants were tested in 14 papers, but since two studies applied more than one task to assess risky behaviour (71,82), the equivalent of 16 trials were considered. Eight trials described positive outcomes (47,82–88), one described negative outcomes (89), two observed both positive and negative results (90,91) and five reported no significant results (39,71,71,82,92). The targets included the dlPFC using unilateral and bilateral tDCS and the OFC. The parameters varied between 0.028 and 0.375 mA/cm² for estimated values of current density and between less

than 15 min up to 30 min for the stimulation duration in single sessions. A trial by Pripfl and colleagues (90) also included smokers in a non-clinical sample and described improvements in the risky behaviour of healthy subjects in 'cold' trials with an anode left/cathode right configuration; in 'hot' trials, an anode right/cathode left configuration increased risky behaviour on subjects who did not smoke, while smokers displayed the opposite behaviour (decreased risk-taking).

The four other papers assessed clinical populations diagnosed with cocaine dependence (93), marijuana use (94), tobacco dependence (95) and gambling disorder (77). Since one study applied two tasks to evaluate risky behaviour (93), five trial results were considered: two obtained positive effects (77,93), one observed a negative outcome (94), one obtained both negative and positive outcomes (93) and the last one observed no effect (95). The dlPFC was the only target, both unilaterally and bilaterally. The current densities varied between 0.046 and 0.057 mA/cm², and stimulation was carried out over 15–30 min in single or multiple sessions.

3.3. Planning

Three papers assessed planning ability, and significant improvements were reported by all of them (Table 3). Only healthy participants took part in these studies (47,96,97). The current densities ranged from 0.028–0.042 mA/cm², and stimulation lasted for 15–20 min over the course of one or three sessions. The Tower of London task was applied by Dockery and colleagues (96) during and after three sessions of unilateral stimulation over the left dlPFC. They observed an effect related to the session order, with significant improvements on planning ability when cathodal stimulation sessions were followed by anodal sessions. In addition, effects were persistent for six to 12 months.

3.4. Delay Discounting

Seven papers investigated tDCS's impact on delay discounting (Table 4). Six of them included healthy participants, with the equivalent of seven trials analysed since one paper tested both conventional and HD-tDCS (98). Positive effects were reported by two studies (47,87), while one study reported a negative outcome (99), one described both positive and negative outcomes (98) and three others observed no significant effect (98,100,101). Parameters were as follows: Current densities between 0.042–0.177 mA/cm², and a duration of 20–30 min carried out in single sessions. The dlPFC was once more the only target, both unilaterally and bilaterally.

However, only one trial evaluated this dimension in a clinical population. Kekic and collaborators (102) assessed the impact of tDCS on the delay discounting of 39 patients diagnosed with bulimia nervosa. They observed that bilateral stimulation of the dlPFC in both anode right/cathode left and anode left/cathode right configurations (0.08 mA/cm², 20 min) increased self-regulatory control on a temporal discounting task (102).

3.5. Craving

Thirty-five studies assessed the impact of tDCS on craving (Table 5). Six of them focused on healthy subjects, all of whom had their food cravings measured. Five reported positive effects with a reduction of cravings (70,100,103–105), while one did not observe significant effects (106). They all unilaterally or bilaterally targeted the dlPFC. The current densities ranged from 0.028 to 0.08 mA/cm², and the stimulation was applied over 20 min in single or multiple (up to five) sessions. Ljubisavljevic and co-workers (105) reported the effects persisted after 30 days.

In addition, 29 trials evaluated craving in clinical populations. The effect of tDCS on craving was tested for food (102,107), alcohol (73,80,108–114), tobacco (81,95,115–121), crack cocaine (112,122,123), cocaine (124), methamphetamine (125,126), marijuana (94) and heroin (127). One population tested for tobacco craving was also diagnosed with

schizophrenia (128). The current densities varied between 0.028–0.196 mA/cm² and was applied between 10 and 30 min during one to 10 sessions. Eighteen studies obtained a reduction in craving (80,94,95,102,107,108,110,114–117,119,121–123,126,127,129), one reported both positive and negative outcomes (125) and ten described no significant outcome (73,81,109,111–113,118,120,124,128).

A study by Shahbabaie and colleagues (125) applied anodal stimulation to the right dlPFC and assessed methamphetamine cravings both online and offline (i.e., pre- and post-stimulation). They reported reduction in craving from before to during the stimulation session. However, there was also significant increase in craving during cue exposure in active tDCS sessions when compared to sham sessions. Burgess and collaborators (107) obtained reduction in food craving in relation to binge-eating disorder (BED) following bilateral stimulation of the dlPFC. They observed, however, that the improvement was more significant in men than women, with the effect lasting for 5–6 hours in men only.

4. DISCUSSION

The aim of this review was to analyse evidence on the efficacy of tDCS in reducing impulsivity in healthy and psychiatric populations. The overall clinical effect of tDCS on response inhibition, risk-taking, planning, delay discounting and craving seems encouraging, with 74 papers finding positive results, both in healthy (45 trials) and clinical populations (29 trials). However, our results highlight that those effects may depend on the stimulation parameters (i.e., stimulation target, duration, current density and the use of offline or online protocols), the applied measures of impulsivity and participants' characteristics (see Table 6 for healthy populations and Table 7 for clinical populations).

4.1. tDCS effects on impulsivity's dimensions

4.1.1. Response inhibition

Most trials testing tDCS's impact on response inhibition in healthy individuals target the IFG, dlPFC and pre-SMA. Regarding the IFG, evidence suggests that inhibitory control can be improved by unilateral anodal stimulation over the right hemisphere (38,45,46,53,55,56,66). The associated parameters are variable, with current densities ranging from 0.028 to 0.125 mA/cm², stimulation durations ranging from 10 to 30 min and stimulation applied in either single or multiple sessions. On the other hand, the deterioration of response inhibition or a lack of effect associated with unilateral anodal stimulation of the right IFG were also observed by two studies with similar stimulation parameters (38,64). However, their sample sizes of only 14 and 16 subjects must be taken into consideration as they represent a limiting factor for the generalisability of their findings. Directly comparable protocols were identified in two trials (53,64). However, their results are inconsistent, with either a positive (53) or a negative outcome (64) associated with anodal tDCS over the right IFG. Furthermore, bilateral stimulation over the IFG has been studied in fewer trials, most of which found a lack of effect on response inhibition (38,69).

Another potential target for modulating response inhibition is the dlPFC. Apparently, improvement in response inhibition is associated with unilateral anodal stimulation over the left dlPFC (47,58), while unilateral cathodal positioning over this target has a deleterious effect (62,63,65). The significant improvements resulting from left anodal stimulation are, however, reported in specific circumstances—that is, only when study participants were exposed to high-tempo music during stimulation sessions (58) or had the cathode placed over the right OFC (47). Moreover, effects resulting from stimulation of the right dlPFC are inconsistent. Despite compatible stimulation parameters, each trial assessed response inhibition with a different task, making a direct comparison unfeasible (48,51,72).

The impact of bilateral montage over the dlPFC would also benefit from further study. Positive results were described by three trials using either an anode right/cathode left (52) or

anode left/cathode right configuration (49,50), a current density of 0.057 mA/cm², a session duration of 10–20 min and one or six sessions. The largest among them (49) was conducted on 202 participants that obtained improvements in inhibitory control following anode right/cathode left stimulation. However, one trial that involved 81 participants (the original sample consisted of 198 subjects sorted into two studies) reported no significant effect from bilateral montage (71), although it was conducted using a different task (the Stroop task). Still another trial reported no effect of anode right/cathode left montage on the go/no-go (GNG) task (70), but since it only involved nine subjects, the external validity of its behavioural outcomes may be compromised. Additional research is thus essential to clarify the impact of tDCS on response inhibition when applied to the dlPFC.

More consistency in increasing response inhibition was observed with anodal stimulation over the pre-SMA: current densities of 0.028 to 0.125 mA/cm² applied for 10 to 20 min in single sessions were associated with better performance on the SST (41,42,54,57). Two trials were directly comparable (41,42) and succeeded in replicating the positive outcomes.

Cortical zones such as the IFC (43), IFJ (51), OFC (39), the sMFC (61) and the lPFC (67) were less explored in healthy individuals. Nevertheless, they were associated with significant effects of tDCS on inhibitory control and could represent interesting targets for future trials as well.

Trials assessing response inhibition on clinical populations only tested tDCS's impact on the dlPFC. Results suggest that unilateral anodal stimulation of the left dlPFC may improve inhibitory control in populations diagnosed with alcohol dependence (73,75), methamphetamine use (76), depression (74) and ADHD (78,79). However, protocols were highly variable, with current densities ranging from 0.03 to 0.08 mA/cm² applied in 10 min single sessions or multiples sessions of 13–20 min. There was a lack of correspondence

between tasks (78,79). When it comes to bilateral montage over the dlPFC, there is still insufficient evidence on its effects on response inhibition to draw conclusions. Results are inconsistent in populations with different diagnoses, variable parameters and different tasks applied (76,79).

4.1.2. Risk-taking

The impact of tDCS on risk-taking in healthy individuals was mainly tested on the dlPFC. Once more, studies found that unilateral anodal stimulation over the left hemisphere was associated with improvement (47,87), while cathodal inhibition led to increased risky behaviour (91). Anodal stimulation with both conventional (0.042 mA/cm²) and HD-tDCS was applied for 20 min in these trials. However, cathodal HD-tDCS over the left dlPFC was also found to be associated with a reduction of risky behaviour (86), and a lack of effect was reported following unilateral anodal stimulation with the same task and target (71) at higher current densities (0.057–0.08 mA/cm² and HD-tDCS). Stimulation of the right dlPFC was tested less frequently and with inconsistent results (71,91).

Furthermore, experimenting with bilateral montage is more common than with unilateral montage, although results are again inconsistent, and and both efficacy and the task applied vary. There are almost as many trials that confirmed the association between reduced risky behaviour with an anode right/cathode left configuration (82,83,85,88,90) as there are trials that observed no effect from either montage over the dlPFC (71,71,82,92), the latter of which was conducted on larger samples. Among these, three papers had comparable protocols: one differed only by a shorter session duration, describing an improvement in risky behaviour (85), while the other two reported no significant outcomes (71,82).

The OFC was less explored. However, unilateral anodal stimulation over the OFC's left hemisphere could be associated with a significant reduction in risk-taking (39).

Trials on clinical populations only tested the effects of a bilateral tDCS electrode placement on risk-taking in patients diagnosed with substance use disorders (cocaine, marijuana and tobacco) or behavioural addiction (gambling disorder). The anode right/cathode left montage may be associated with a reduction in risky behaviour in patients with cocaine dependence (93,93) or gambling disorder (77), while the cathode right/anode left configuration seems to increase it (93,94). Different tasks were used to assess tDCS's efficacy, and inconsistent results were observed. A lack of any tDCS effect was reported in tobacco smokers, but this study only had a sample of 12 patients (95).

4.1.3. Planning

Effects on planning performance were also only assessed with stimulation over the dlPFC. There are a limited number of studies, but they show promising effects. Unilateral anodal stimulation over the left hemisphere was associated with improvement (47,96). A current density of 0.028 mA/cm² was applied for 15 min, and a density of 0.042 mA/cm² was applied for 20 min. On the other hand, bilateral montage was associated with improvement if the electrodes were positioned in an anode right/cathode left montage (97). However, this outcome was only observed online.

4.1.4. Delay discounting

The dlPFC was the only tested target in trials composed of healthy participants. Two HD-tDCS studies showed a reduction in temporal impulsivity with unilateral anodal stimulation over the left dlPFC for 20 min both online and offline (87,98), while cathodal inhibition was associated with a deleterious effect (98). The results of conventional tDCS over the left hemisphere, on the other hand, were inconsistent, with improvement associated with both unilateral cathodal and anodal stimulation (47). In addition, tDCS over the right dlPFC may have no significant online outcome on delay discounting, following an assessment of 145

subjects (101). The results of positioning the electrodes bilaterally over the dlPFC showed no consensus. The largest trial, with 117 participants, reported no significant effect (98).

Finally, concerning tDCS's impact on delay discounting in clinical populations, outcomes are limited to one study. The trial suggested that both anode right/cathode left and anode left/cathode right configurations can decrease temporal impulsivity in patients diagnosed with bulimia nervosa (102).

4.1.5. Craving

When healthy subjects were tested for food cravings, the only target was the dlPFC once more. Unilateral anodal stimulation over the right hemisphere was associated with reduction of craving (105). A bilateral montage with an anode right/cathode left configuration may also result in positive effects, as reported by four trials (70,100,103,104), among which two applied directly comparable protocols (70,103). However, the studies used small sample sizes, and a trial with a larger sample described a lack of effect with the same electrode positioning (106). Both unilateral and bilateral montages would thus benefit from further investigation.

Craving outcomes in clinical populations were mostly assessed with the dlPFC as the target. Unilateral anodal stimulation was tested on alcohol and tobacco cravings. For the first condition, there was no consensus on whether effects were positive or non-significant with anode placement over the left dlPFC. Although the stimulation parameters did not differ much, nearly every trial had a different assessment tool (either questionnaires or tasks) (73,80,109–111). Two directly comparable protocols did not successfully replicate each other's findings (80,109).

On the other hand, there is more consistent evidence that unilateral anode stimulation over the left dlPFC can reduce tobacco craving (115–117,121) with current densities between 0.028 and 0.057 mA/cm² applied for 20 to 30 min in one or five sessions. Two of these trials

obtained directly comparable data and were consistent on reporting improvements (115,117). Nonetheless, similar parameters were also applied without success concerning tobacco craving with conventional tDCS (81,118), HD-tDCS (120), or in a sample of smokers also diagnosed with schizophrenia (128). The right hemisphere was less frequently targeted for tobacco craving (119) and methamphetamine use (125), so the data remain insufficient.

Bilateral montages were the most common method. An anode right/cathode left configuration over the dlPFC was associated with craving reduction in the following conditions: bulimia (102), BED (107), alcohol dependence (108,114,129), tobacco dependence (95), crack cocaine dependence (122), methamphetamine dependence (126) and marijuana use (94). The current density was often 0.057 mA/cm² (studies on eating disorders applied 0.08 mA/cm²) applied for 15 to 30 min in single or multiple sessions. Further investigation is still needed since some of these studies counted on small samples and since inconsistent results have also been reported by other trials (112,113,120,124).

Lastly, an unusual configuration (cathode right/cathode left) over the frontal-parietal-temporal cortex showed a reduction in heroin cravings (127). This result once more puts forward that research concerning the application of tDCS (and its ideal parameters) to treat impulsivity is far from being comprehensive.

4.2. Factors influencing tDCS's effects

4.2.1. Measures of impulsivity

As discussed extensively in several excellent reviews of the taxonomy of impulsivity that conceptualise its multidimensional nature (1,3,9), the tools employed to measure impulsivity probably reflect separate underlying processes (5,37,130,131). In the included studies, the instruments used to assess impulsivity are variable and rely on three classes: (a) self-report measures, (b) behavioural laboratory measures and (c) neuropsychological

assessment (6,7). The first class involves a subjective rating of the extent to which particular items describe long-term personality traits of the individual. The second one corresponds to objective methods, suitable for repeated-use and treatment studies, based on two animal models of impulsivity: the inability to delay reward and the inability to conform responses to the environmental context (5). The third class includes neuropsychological measures involving assessments by technological devices while the subjects perform tasks through techniques such as event-related potentials, neuroimaging and NIBS (6,7).

Each of these classes presents limitations regarding the measurement of impulsivity. Self-rated scales, such as the Barratt Impulsiveness Scale (BIS) or craving questionnaires, are not suitable for repeated administration and are susceptible to an individual's biases, such as low self-awareness concerning their behaviour (7). Besides, they measure relatively stable characteristics, making them hard to relate to physiologic or pharmacologic studies (5). Laboratory measures, such as the GNG task or the SST, try to overcome these limitations. However, while they are objective and appropriate for comparative studies, they do not measure long-term traits, and they do not incorporate social aspects of impulsivity (6). Lastly, neuropsychological assessment has emerged as an objective method with great potential to establish links to the underlying neural mechanisms implicated in impulsive behaviour (7). Nonetheless, neuropsychological assessments also do not include social aspects of impulsivity, and the results could be influenced by neuropsychiatric conditions as well since they are not specific measures (6).

As a possible way to overcome limitations and aim for a consistent assessment of impulsivity, some studies combined different instruments. Nejati and collaborators (47) observed simultaneous improvements on response inhibition, planning ability, risky behaviour and delay discounting in healthy participants with different electrode montages. In addition, Cheng and Lee (82) applied the risky-gains task (RGT), the Balloon Analogue Risk Task

(BART), the Stroop task and the BIS on a healthy population. Although the RGT resulted in improvements under stimulation and although its results were positively correlated with the Stroop task and the attentional impulsiveness subscale of the BIS, no significant outcomes were observed with the BART. Yet, the BART also supposedly assessed the risk-taking dimension. Ouellet and colleagues (39) found improvements in risky decision-making through the Iowa gambling task and in response inhibition by the Stroop task; however, their assessment of response inhibition by the SST did not provide evidence for the impact of tDCS.

These examples demonstrate a lack of correlation between tasks and their evaluated outcomes, suggesting a heterogeneous manifestation of the multiple dimensions of impulsivity as well. In accordance with this observation, Dalley and colleagues (2) described a general lack of intercorrelation between these objective methods, explaining that although they shared common features, such as the evaluation of inhibitory control, this inhibition could be required at different moments in the programming of response output, being thus implemented by different neural structures and resulting in different expressions of impulsivity at the behavioural level.

4.2.2. Stimulation parameters

Regarding stimulation parameters, key elements such as the current density, electrodes' position, polarity and stimulation duration are apparently also associated with the efficacy of neuromodulation by tDCS. A great variety of parameter combinations was observed in trials assessing healthy subjects, while studies focussing on psychiatric patients showed slightly more uniformity among their protocols.

The diversity of chosen parameters combined with several impulsivity-measuring instruments makes it hard to establish consistent comparisons between trials and their outcomes. Among the few studies that we identified as having directly comparable protocols,

three pairs reported consistent findings with improvement in response inhibition in association with pre-SMA anodal stimulation (41,42); food cravings, with dlPFC bilateral anode right/cathode left stimulation (70,103); and tobacco cravings, with anodal stimulation over the left dlPFC (114,116; further parameters on Tables 1 and 5). A lack of comparable studies available in the tDCS literature and the unreliability of the cognitive effects of a single tDCS session have been previously observed (132,133). This scenario reinforces the need to review the tDCS literature as a means of contributing to the further development of tDCS protocols and homogeneity of parameters.

As reviewed in 2008 (30), the current density delivered by most tDCS studies varied between 0.029 and 0.08 mA/cm², and these limits have expanded since then. Our reviewed articles showed estimated current densities that ranged from 0.028 to 0.375 mA/cm² (0.028 to 0.196 mA/cm² in clinical populations)—the higher values belonging to HD-tDCS—with no associated main adverse effects. As noticed in the articles, higher current densities do not independently imply a stronger stimulation outcome, and this element should be interpreted in context with other tDCS parameters. Current density does not always have a linear relationship with the strength of effects, as higher densities could increase the electrical field and differently activate superficial and underlying cortical layers (30).

The duration of sessions varied between 4.12 and 30 min (10 to 30 min in clinical populations). A longer persistence of effects was observed in healthy subjects after sessions lasting either 15 or 20 min (49,96,105). With repeatedly performed sessions in short intervals, a cumulative effect was observed as well (46). Usually, aftereffects are associated with at least 10 min of stimulation with a constant current density, although the persistence of these effects may depend on the targeted area (30).

Most trials' choice of targets was consistent with the current evidence of the PFC's crucial role on cognitive control of behaviours and impulsivity, as its neural substrates have

mainly been studied in relation to inhibitory control (2). A variety of electrode configurations over targets was observed, and the results were sometimes conflicting. The fact that tDCS is not precise enough to target one specific brain area (30) should be taken in account when analysing conflicting results. Distinct neuronal networks could be simultaneously modulated depending on the electrodes' configuration (2). Lefacheur and co-workers (33) described extra-local effects identified by other experiments, such as interference with functional connectivity, synchronisation and oscillatory activities in various networks, which has also been shown in the PFC. They still reported that different effects can be obtained when comparing cortical layers: anodes could preferably stimulate the underlying cortex, while cathodes impact the superficial cortex instead (33). In addition, subtle effects could be associated with a redirection of sources, such as blood flow, to the actively stimulated area, as suggested by Iyer and colleagues (29). Improvements would therefore also be related to these effects, restoring local functions in subjects with impairments, such as reduced attention.

Furthermore, bilateral and unilateral stimulation should not be expected to have similar outcomes. The focality of tDCS is additionally limited by bilateral stimulation and larger electrode areas (30). Extracephalic reference electrodes could therefore avoid the confounding effects of bilateral stimulation, as well as smaller-sized electrodes (e.g., by reducing the amount of shunting in the scalp and having a greater edge effect relative to the electrode surface) (30).

4.2.3. Population characteristics

An often-overlooked point is the population on which tDCS is applied. The interaction of stimulation polarity, cognitive domain and other intra- and inter-individual variables—such as gender, anatomic or genetic factors (62,68,107,134), personality (72,90,100,135–137), cognitive strategy (138) and baseline neuronal activation state (96)—need to be taken into consideration. Most of the included studies included both smokers and non-smokers in their

population; however, it was observed that opposite outcomes in risk-taking could be obtained after bilateral dlPFC stimulation depending on whether the subject smoked or not (90). Similarly, it was shown that Lesch's type IV alcohol-dependent subjects would be more responsive to tDCS's effects on inhibitory control, when compared to alcohol-dependent patients classified under other types (73). Furthermore, a dependency of the effect on baseline neuronal activation state was observed by Dockery and colleagues (96), who identified enhancement on planning performance only when cathodal stimulation preceded anodal stimulation. The population's characteristics and sequence of sessions should therefore be carefully specified since they may have an impact on stimulation outcomes.

5. CONCLUSION

The current review enables recommendations to be drawn together for clinical and research perspectives, including the need to minimise heterogeneity by using highly validated and reliable cognitive tasks, and the need for more research to determine the optimal parameters of stimulation. Combining a translational approach in clinical trials together with imaging and cognitive measures should also be considered. Moreover, further research is equally required to develop a more comprehensive understanding of impulsivity, allowing for an accurate assessment of its behavioural outcomes and a definition of protocols regarding tDCS application as a therapeutic tool for impulsive disorders.

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The authors have no conflict of interest to disclose.

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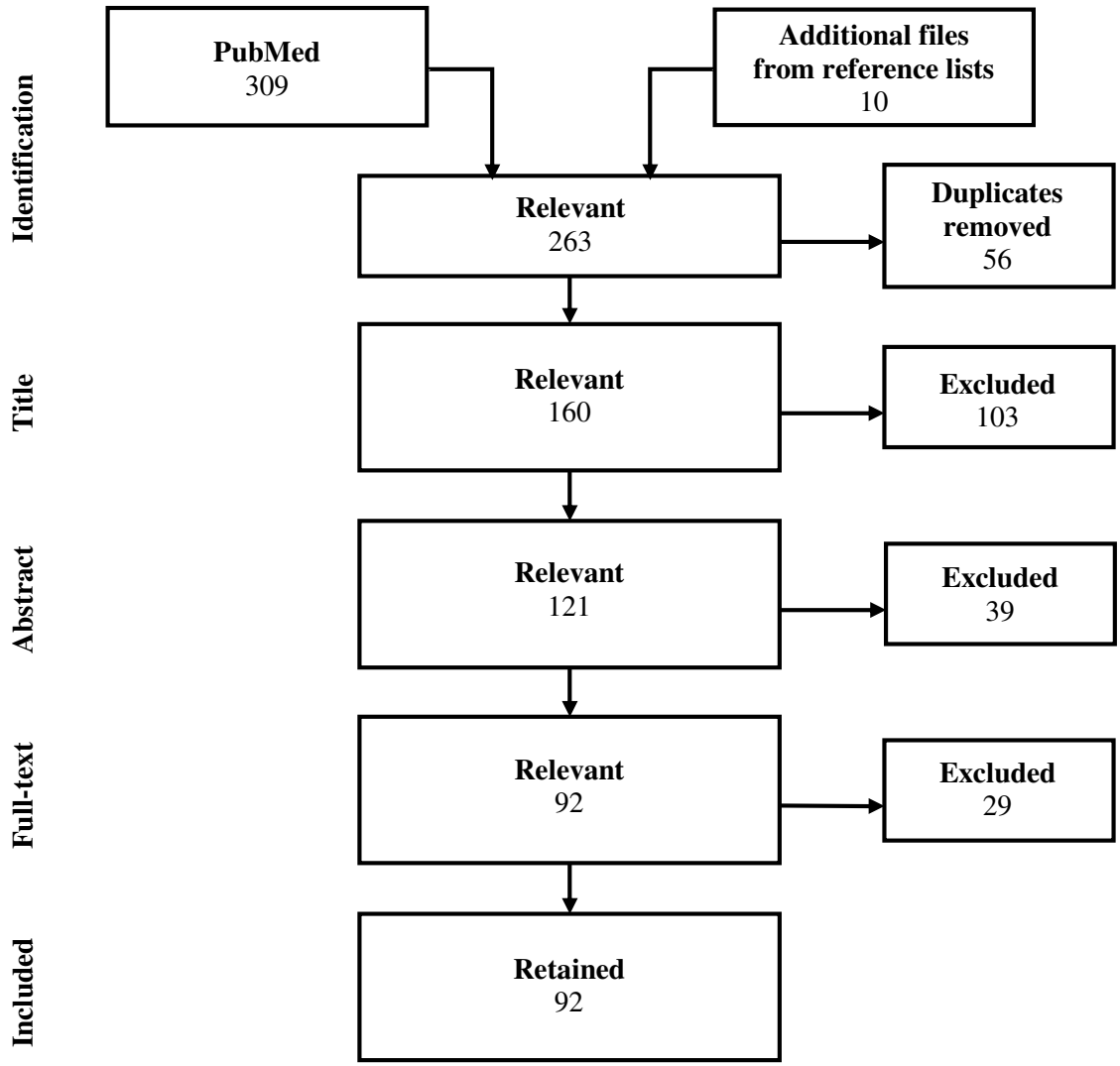

Figure 1. Results obtained on each phase of the systematic review following PRISMA recommendations (35).

Table 1. Detailed information of included studies that assessed tDCS impact on response inhibition of healthy and clinical populations.

Authors	Design	Subjects	Task	tDCS parameters						Results
				Online / Offline	Polarity	Electrode position	Surface	Intensity	Duration	
RESPONSE INHIBITION										
Healthy populations										
Beeli G, Casutt G, Baumgartner T, Jäncke L	Randomized sham-controlled within-subjects	35 [17 F; mean age 24.9 yo; all RH]	Go/No-Go task	Online	A/C/S	F3 + ipsilateral mastoid	35 cm²	1.5 mA	5.5 min (3.5 min intersession)	C: ↑false alarms (tendency impulsive behavior) vs S and vs A
Bender AD, Filmer HL, Dux PE	Randomized sham-controlled within-subjects	Exp 1: 18 [12 F, mean age 24 yo, all RH]; Exp 2: 18 [12 F, mean age 21 yo]; Exp 3: 36 [25 F, mean age 22 yo]	Exp 1: response selection training; Exp 2: Stop-Signal Test; Exp 3: Colour / symbol / sound discrimination task	Offline (pre-, immediately post- and 30 min post-tDCS)	A/C/S; Exp 3: C/S	1 cm posterior to Fz + right mastoid	25 cm²	0.7 mA	Exp 1 and 2: 9 min; Exp 3: 13 min (48h intersessions)	(1) Exp 1: no differences in RTs between A, C and S; (2) Exp 2: C stimulation elongated RTs to no-signal trials vs A and sham; (3) Exp 3: C stimulation prolonged no-signal RTs in the inhibitory context but not in the non-inhibitory context
Cai Y, Li S, Liu J, Li D, Feng Z, Wang Q, Chen C, Xue G	Randomized controlled within-subjects	22 [10 F; 22.6 ± 3 yo]	Stop Signal Task	Offline (pre- and post-tDCS)	A	Right IFG: A on the middle of F4 and F8 / right IPL: A on P4 / VC (control group): A on Oz + reference over left cheek	25 cm²	1.5 mA	15 min (48h intersessions)	(1) ↑PC and ↓SSRT post right IFG stimulation; (2) No significant difference between right IPL and VC stimulation
Campanella S, Schroder E, Monnart A, Vanderhasselt M-A, Duprat R, Rabijns M, Kornreich C, Verbanck P, Baeken C	Randomized sham-controlled double-blind	31 [all M; mean age 21.9 ± 3.1 (active group), 21.3 ± 1.7 (sham group) yo]	Go/No-Go Task	Offline (pre- and post-tDCS)	A/S	A: F8 (right IFG) + reference superior region of the trapezius muscle (neck)	25 cm²	2 mA	20 min	(1) ↓RT in sham group vs active; (2) No impact of stimulation condition on performance at the behavioral level
Campanella S, Schroder E, Vanderhasselt M-A, Baeken C, Kornreich C, Verbanck P, Burle B	Randomized sham-controlled double-blind between-subjects	35 [all M; mean age 22.2 ± 3.0 (active group), 21.3 ± 1.7 (sham group) yo]	Go/No-Go Task	Offline (pre- and post-tDCS)	A/S	A: F8 (right IFG) + reference superior region of the trapezius muscle (neck)	25 cm²	2 mA	20 min	Active tDCS: ↓drop in accuracy for fast responses (↓impulsivity and ↑inhibitory efficiency)
Castro-Meneses LJ, Johnson BW, Sowman PF	Randomized sham-controlled	14 [11 F; all RH; mean age 22 ± 3.9 yo]	Stop Signal Task	Online and offline (pre- and post-tDCS)	A/S	A: intersection point between T4-Fz and F8-Cz + C: left cheek	25 cm²	1.5 mA	15 min	(1) ↓Reactive inhibition during anodal tDCS vs sham in both manual and vocal modalities; (2) No effect on go-RTs (proactive inhibition)
Cunillera T, Brignani D, Cucurell D, Fuentemilla L, Miniussi C	Randomized sham-controlled	23 [14 F; all RH; mean age 25 ± 3.6 yo]	Go/No-Go-Stop Signal Task	Online	A/S	A: intersection point between T4-Fz and F8-Cz + C: crossing point between T3-Fz and F7-Cz	9 cm²	1.5 mA	20 min	(1) A: modulate RTs (↑proactive inhibition); (2) ERP: tDCS ↓amplitude of inhibitory-P3 in No-Go and Stop correct inhibited trials
Dambacher F, Schuhmann T, Lobbestael J, Arntz A, Brugman S, Sack AT	Randomized sham-controlled	64 [25 F; mean age 21.89 ± 3.26 yo]	Go/No-Go Task	Online	A/C/S	F7 + F8	35 cm²	1.5 mA	21.75 min	(1) No main effects of stimulation; (2) M displayed more proactive aggression than F
Ditye T, Jacobson L, Walsh V, Lavidor M	Randomized sham-controlled	22 [14 F; mean age 23.58 yo; all RH]	Stop Signal Task	Offline (SST post-tDCS)	A/S	A: crossing point T4-Fz and F8-Cz / C: above left eyebrow	35 cm²	1.5 mA	15 min (4 sessions/day, except 5th day)	tDCS group: ↑performance in 3rd and 4th days vs sham

Filmer HL, Lyons M, Mattingley JB, Dux PE	Pseudo-randomized sham-controlled between-subjects single-blind	59 [51 F; all RH; mean age 21 ± 2 yo]	Go/No-Go Task	Offline (pre- and post-tDCS: 1 day and 2 weeks after)	A/C/S	1 cm posterior to F3 + reference contralateral orbitofrontal region	25 cm²	0.7 mA	13 min (4 sessions, 24h intersessions)	No main effects of stimulation condition
Friehs MA, Frings C	Randomized sham-controlled between-subjects	56 [35 F; all RH; mean age 24.82 ± 3.78]	Stop Signal Task	Offline (pre- and post-tDCS)	A/S	A: F4 + reference: left deltoid muscle	A: 9 cm² + C: 35 cm²	0.5 mA	19 min	Significant ↓ SSRT after A stimulation (inhibition process enhanced)
Gómez-Ariza CJ, Martín MC, Morales J	Randomized sham-controlled	164 [all RH]	AX-CPT (proactive and reactive control)	Online and offline (pre- and post-tDCS)	A/C/S	F3 / F4 / FC6h (midway between FC4 and FC6 - right IFJ) + reference: contralateral shoulder	35 cm²	2 mA	20 min	(1) Online: anodal right IFJ ↓proactive indices vs sham; (2) Offline: cathodal right dlPFC ↓proactive indices vs anodal right IFJ and sham; (3) No effect over left dlPFC
Hogeveen J, Grafman J, Aboseria M, David A, Bikson M, Hauner KK	Randomized controlled	46 [groups mean age of 26.13 and 23.44; close matches for gender and handedness]	Stop Signal Task	Offline (pre- and post-tDCS)	A	pad-IFC: A: FC6 + C: Cz / HD-IFC: A: FC6 + C: F10, CP2, TP8, and F2 / pad-Oz (control): A: Oz + C: Cz	tDCS: 35 cm² / HD-tDCS: (4x1) 1 cm diameter	1 mA	20 min	HD-tDCS and conventional tDCS over IFC: statistically similar effects on ↑response inhibition performance vs control
Hsu T-Y, Tseng L-Y, Yu J-X, Kuo W-J, Hung DL, Tzeng OJL, Walsh V, Muggleton NG, Juan C-H	Randomized sham-controlled within-subjects	28 [12 F; range 18-27 yo]	Stop Signal Task	Offline (pre-tDCS) + online	A/C/S	Fz (pre-SMA) + left cheek	16 cm²	1.5 mA	10 min (24h intersession)	A: ↓noncancelled response rates, C: ↑
Jacobson L, Javitt DC, Lavidor M	Randomized sham-controlled single-blind	22 [16 F; all RH; mean age 28.3 ± 6.8 yo]	Stop Signal Task	Offline (post-tDCS)	A/C/S	Crossing T3-Fz and F7-Cz / T4-Fz and F8-Cz + contralateral orbito-frontal cortex (above eyebrow), crossing T3-Fz and F7-Cz + crossing T4-FZ and F8-Cz	25 cm²	1 mA	10 min (1 week intersession)	(1) Unilateral A right ↓SSRT (better inhibition abilities) compared with sham and bilateral A left/C right; (2) Unilateral C right ↑SSRT compared with bilateral C right/A left
Kelley NJ, Schmeichel BJ	Randomized sham-controlled between-subjects double-blind	202 [107 F; all RH; mean age 19.1 ± 1.5 yo]	Approach-Avoidance Task	Offline (pre- and post-tDCS)	A/C/S	F4 + F3	35 cm²	2 mA	15 min	Right A/left C showed ↓RT (faster to pull negative images toward the self and push positive images away) vs left A/right C and sham
Kwon YH, Kwon JW	Randomized sham-controlled between-subjects	40 [20 F; mean age 23.0 ± 1.8 yo]	Stop Signal Task	Online and offline (pre- and post-tDCS)	A/S	A: 4 cm anterior to Cz + C: left cheek	35 cm²	1 mA	10 min	Significant ↓stop processing-times during and after stimulation
Kwon YH, Kwon JW	Randomized sham-controlled within-subjects	40 [18 F; 22.97 ± 2.21 yo]	Stop Signal Task	Offline (pre- and post-tDCS)	A/S	A: C4 / C3 / 4 cm anterior to Cz + C: contralateral supraorbital area	35 cm²	1 mA	10 min (24h intersession)	↓SSRT under the pre-SMA condition compared to both M1 and sham

Lapenta OM, Sierve KD, de Macedo EC, Fregni F, Boggio PS	Randomized sham-controlled double-blind crossover	9 [all F; mean age 23.4 ± 2 yo; normal range for BMI]	Go/No-Go Task + Visual Analogue Scale for the urge to eat	VAS: online and offline (pre- and post-tDCS) + GNG: offline (post-tDCS)	A/S	A: F4 + C: F3	35 cm²	2 mA	20 min	(1) GNG: no main effects of stimulation; (2) ↓Craving post-stimulation
Leite J, Gonçalves ÓF, Pereira P, Khadka N, Bikson M, Fregni F, Carvalho S	Randomized sham-controlled within-subjects	16 [11 F; all RH; mean age 21.5 ± 4.5 yo]	Prepotent response inhibition task + Choice Reaction Time + Go/No-Go Task	Offline (3 min post-tDCS)	A/S	A: right IFG + C: left IFG	A + C: 35 cm² (bilateral) / A: 35 cm² + C: 100 cm² (unilateral)	1 mA	30 min (72h intersession)	(1) PRIT: unilateral ↑accuracy but ↓response speed when comparing to bilateral and sham; (2) No significant effects on other performances
Li LM, Violante IR, Leech R, Hampshire A, Opitz A, McArthur D, Carmichael DW, Sharp DJ	Randomized sham-controlled whithin-subjects	26 [13 F; mean age 38 ± 15.5 yo]	Stop Signal Task	Online	A/C/S	F8 (right IFG) + return: right shoulder	Active: ~16 cm² + return: 35 cm²	2 mA	4 min 12 sec (3 sessions, 2-3 min intersessions)	Significant ↓SSRT during A stimulation vs S (by improvement on the SSD); no difference between C vs S or A vs C
Loftus AM, Yalcin O, Baughman FD, Vanman EJ, Hagger MS	Randomized sham-controlled between-subjects	28 [18 F; all RH; mean age 24.5 yo]	Stroop Task	Offline (pre- and post-tDCS)	A/S	A: F3 + C: F4	35 cm²	2 mA	10 min	↓Reaction times without increase in errors (↑inhibitory control)
Mansouri FA, Acevedo N, Illipparampil R, Fehring DJ, Fitzgerald PB, Jaberzadeh S	Randomized sham-controlled within-subjects	73 [37 F; all RH; 18-32 yo]	Stop Task	Offline (pre- and post-tDCS)	A/S	A: F3 + C: right supraorbital area	A: 10 cm² + C: 24 cm²	1.5 mA	10 min (with high-tempo, low-tempo, or no-music as background noise)	↓SSRT in high-tempo music condition after anodal stimulation when compared to sham
Metzuyanim-Gorlick S, Mashal N	Randomized sham-controlled between-subjects	20 [11 F; mean age 30.8 yo; 12 years education]	Hayling task	Offline (pre- and post-tDCS)	A/S	A: F3 + C: F4	35 cm²	2 mA	20 min (6 sessions in 2 weeks, 3/week)	(1) ↑Inhibition of a dominant response; (2) Effect lasted for 1 month
Nejati V, Salehinejad MA, Nitsche MA	Randomized sham-controlled within-subjects single-blind	24 [all M; mean age 26.75 ± 1.89 yo]	Go/No-Go Task + Tower of Hanoi Task + Balloon Analogue Risk Task + Temporal Discounting Task	Online	A/C/S	F3 + Fp2	35 cm²	1.5 mA	20 min (72h intersession)	(1) GNG: A left-dlPFC/C right-OFC ↑No-Go accuracy responses and ↓RT; (2) TOH: both conditions ↓total time of problem solving and A left/C right ↓number of false moves; (3) BART: A left/C right ↓risk taking; (4) TDT: both conditions ↓temporal discounting rate
Nieratschker V, Kiefer C, Giel K, Krüger R, Plewnia C	Randomized sham-controlled double-blind crossover	41 [32 F; all RH; mean age 24 ± 4.2 yo]	Go/No-Go Task	Online	C/S	C: F3 + A: above right orbit	35 cm²	1 mA	20 min	(1) Significant interaction between COMT genotype Val/Val,Met and stimulation: within the Val/Val group, response inhibition was significantly impaired under C stimulation vs S. C stimulation had no effect on Met-carriers; (2) No significant effects over sustained attention and set-shifting
Oldrati V, Patricelli J, Colombo B, Antonietti A	Randomized sham-controlled between-subjects double-blind	39 [24 F; mean age 25.28 ± 8.04 yo; 6 LH]	Cognitive Reflection test (CRT) + Dickman Impulsivity Inventory (DII) + Barratt Impulsivity Scale (BIS-11)	Offline (post-tDCS)	A/C/S	F3 + reference over right deltoid muscle	25 cm²	1.5 mA	20 min	(1) DII/BIS: no group differences; (2) CRT: C↑tendency to respond impulsively; (3) Both: motor impulsivity negatively associated with number of correct responses

Ouellet J, McGirr A, Van den Eynde F, Jollant F, Lepage M, Berlim MT	Randomized sham-controlled single-blind between-subjects	45 [29 F; mean age 25.09 ± 7.10 yo; mean years of education 16.89 ± 2.41]	Iowa Gambling Task (IGT) + Balloon Analog Risk Task (BART) + Stroop task + Stop Signal Task (SST)	Offline (pre- and post-tDCS)	A/S	A: Fp1 + C: Fp2	A:35 cm², C: 55.25 cm²	1.5 mA	30 min	(1) IGT: ↑advantage on choices; (2) Stroop: ↓interference scores, with no effect on humor or attentional levels; (3) SSRT not influenced; (4) BART: trend to intervention x time interaction
Plewnia C, Zwissler B, Längst I, Maurer B, Giel K, Krüger R	Randomized sham-controlled double-blind crossover	46 [21 F; all RH; mean age 25.87 ± 7.29 yo]	Go/No-Go Task	Online	A/S	A: F3 + C: above right orbit	35 cm²	1 mA	20 min	(1) ↓Set-shifting ability after A stimulation in the COMT Met/Met homozygotes vs S and Val carriers; (2) No significant effects over sustained attention and response inhibition
Russo R, Twyman P, Cooper NR, Fitzgerald PB, Wallace D	Randomized sham-controlled double-blind between-subjects	198 [Study #1: 117; 68 F; mean age 21.14 ± 2.7 yo; 5 LH / Study #2: 81; 51 F; all RH]	Study #1: Balloon Analogue Risk Task / Study #2: Stroop Task + Balloon Analogue Risk Task	BART: online / Stroop: offline (pre- and post-tDCS)	A/C/S	Study #1: F4 + F3 / Study #2: F4 + F3 or A: F4 / F3 + C: contralateral supraorbital area	Study #1: 25 cm² or 35 cm² / Study #2: 35 cm²	2 mA	Study #1: 30 min / Study #2: 20 min	Study #1: (1) no significant difference between conditions vs sham (right A/left C apparently ↑risk taking); Study #2: (2) no effect observed on Stroop Task or BART; (3) Combined data from both studies showed no significant differences between conditions
Schroeder PA, Pfister R, Kunde W, Nuerk H-C, Plewnia C	Randomized sham-controlled crossover	72 [55 F; all RH; mean age 23.9 yo; 24 subjects/experiment]	SNARC task (control: Simon task)	Online	A/C/S	Experiment #1: C: F3 + A: contralateral upper arm (m. deltoideus) / Experiment #2: idem / Experiment #3: A: F3 + C: contralateral upper arm (m. deltoideus)	35 cm²	1 mA	25 min	↓RT in incongruent SNARC trials during cathodal tDCS (↓interference of task-irrelevant but distracting space–number associations)
Spieser L, van den Wildenberg W, Hasbroucq T, Ridderinkhof KR, Burle B	Randomized sham-controlled within-subjects single-blind	24 [18 F; mean age 22 yo]	Stimulus-response compatibility (SRC) task + EMG activity of flexor pollicis brevis	Online	A/C/S	Active 4 cm anterior to Cz, return left cheek	35 cm²	1 mA	20 min (48h intersession)	(1) No tDCS effect on covert impulsive action tendencies (partial error analysis); (2) Improved accuracy under cathodal stimulation (overt responses analysis)
Stramaccia DF, Penolazzi B, Sartori G, Braga M, Mondini S, Galfano G	Randomized sham-controlled between-subjects single-blind	115 [86 F; 23.37 ± 2 yo]	Stop Signal Task (SST)	Offline (15 min post-tDCS)	A/C/S	Active intersection between T4-Fz and F8-Cz (rIFG) / F4 (rDLPFC) + reference above left supraorbital area	16 cm²	1.5 mA	20 min	Anodal rIFG ↓SSRT (better inhibitory performance)
Weidacker K, Weidemann CT, Boy F, Johnston SJ	Randomized sham-controlled within-subjects single-blind	18 [9 F; all RH; mean age 22.06 yo]	Parametric Go/No-Go Task + Psychopathic Personality Inventory-Revised	Online + PPI-R: offline (pre-tDCS)	A/C/S	F4 + left biceps	25 cm²	1.5 mA	20 min (2-9 days intersessions)	(1) No significant effect on RT or accuracy; (2) ↑Coldheartedness score associated with ↑performance on response inhibition task at highest difficulty level following cathodal stimulation vs anodal vs sham

Yu J, Tseng P, Hung DL, Wu S-W, Juan C-H	Randomized sham-controlled crossover	31 [Study #1: 8; 3 F; age range 20-31 yo / Study #2: 23; 10 F; 20-28 yo]	Stop Signal Task	Study #1: offline (pre- and post-tDCS) / Study #2: offline (during sham and post-tDCS)	A/S	A: Fz + C: left cheek	A: 16 cm² + C: 35 cm²	2 mA	20 min	↑Inhibitory control after anodal stimulation over the pre-SMA vs sham
Clinical populations										
Allenby C, Falcone M, Bernardo L, Wileyto EP, Rostain A, Ramsay JR, Lerman C, Loughead J	Randomized sham-controlled double-blind crossover	37 [11 F; mean age 31.7 yo; ADHD diagnosis; 17 patients reported use of stimulant medication; 48.6% completed high school or some college]	Conners' Continuous Performance Task + Stop Signal Task	Offline (pre-, post-first session and 3 days post-tDCS treatment follow-up)	A/S	A: F3 + C: right supra-orbital area	25 cm²	2 mA	20 min (3 sessions, 2 weeks intersessions)	(1) CPT: ↓false positive errors (↑performance on impulsivity measure), effect was not persistent on follow-up; (2) SST: There was no significant stimulation condition by session interaction for change in SSRT
Boggio PS, Bermpohl F, Vergara AO, Muniz ALCR, Nahas FH, Leme PB, Rigonatti SP, Fregni F	Randomized sham-controlled double-blind between-subjects	26 [18 F; mean age 48.7 yo; unipolar major depressive disorder diagnosis]	Affective Go/No-Go Task	Offline (pre- and post-tDCS at first session)	A/S	A: F3 (active + sham), 2cm midline above inion (active); C: right supraorbital area (frontopolar)	35 cm²	2 mA	20 min (10 sessions, 24h intersession)	A: F3/C: right frontopolar: ↑performance after first session (accuracy)
Cosmo C, Baptista AF, de Araújo AN, do Rosário RS, Miranda JGV, Montoya P, de Sena EP	Randomized sham-controlled double-blind between-subjects	60 [ADHD diagnosis; range 18-65 yo]	Go/No-Go task	Offline (pre- and post-tDCS)	A/S	A: F3 + C: F4	35 cm²	1 mA	20 min	No significant difference pre- and post-tDCS between groups
da Silva MC, Conti CL, Klauss J, Alves LG, do Nascimento Cavalcante HM, Fregni F, Nitsche MA, Nakamura-Palacios EM	Randomized sham-controlled between-subjects single-blind	13 [Lesch's type IV alcohol-dependents, average 49 yo]	Go/No-Go task [FAB]	Offline (pre- and post-five week treatment)	A/S	A: F3 + C: right supradeltoid area	35 cm²	2 mA	20 min (5 sessions, 1 week intersession)	FAB: improved executive function (does not specify tasks)
den Uyl TE, Gladwin TE, Lindenmeyer J, Wiers RW	Randomized sham-controlled double-blind between-subjects	83 [23 F; mean age 48.6 yo; alcohol-dependent patients]	Alcohol Attentional Bias Modification Task + Penn Alcohol Craving Scale	ABM: Online + PACS: Offline (pre- and post-tDCS, 1 to 7 days after last session)	A/S	A: F3 + C: F4	A: 35 cm² + C: 100 cm²	2 mA	20 min (4 sessions within 1 week)	(1) ABM: no beneficial effects of tDCS on changing attentional bias were found; (2) PACS extremely low reported craving; ↓ from preassessment to postassessment
Nakamura-Palacios EM, de Almeida Benevides MC, da Penha Zago-Gomes M, de Oliveira RWD, de Vasconcellos VF, de Castro LNP, da Silva MC, Ramos PA, Fregni F	Randomized sham-controlled crossover single-blind	49 [4 F; mean age 48.8 ± 8.9 yo; alcohol-dependence diagnosis; Lesch's type I (16), II (7), III (14) and IV (12)]	Go/No-Go task [FAB] + Obsessive Compulsive Drinking Scale	Offline (pre- and post-tDCS)	A/S	A: F3 + C: contralateral supradeltoid area	35 cm²	1 mA	10 min	(1) Significant ↑FAB scores after active tDCS for Lesch's type IV group only; (2) No significant effects on craving

Shahbabaie A, Hatami J, Farhoudian A, Ekhtiari H, Khatibi A, Nitsche MA	Randomized sham-controlled double-blind parallel	90 [all M; all RH; mean age 30.76 ± 6.178 yo; early abstinent methamphetamine users; history of at least 12 months methamphetamine consumption, for at least 3 days/week in the last month]	Pictorial Probe Detection Task (PDT)	Offline (pre- and post-tDCS)	A/C/S	A: F3 + C: right shoulder / A: F4 + C: left shoulder / A: F3 + C: right supraorbital ridge / A: F4 + C: left supraorbital ridge / A: F3 + C: F4 / Sham: A: F4 + C: F3	35 cm²	2 mA	26 min (1 session with 20 min no stimulation interval - 13:20:13 schedule)	A: left dlPFC + C: right shoulder / right dlPFC significantly ↓ engagement bias toward drug cues vs S
Soyata AZ, Aksu S, Woods AJ, İşçen P, Saçar KT, Karamürsel S	Randomized sham-controlled triple-blind parallel	20 [all M; all RH; mean age 37.2 ± 10.3 yo; gambling disorder diagnosis]	Iowa Gambling Task (IGT) + Wisconsin Card Sorting Test (WCST)	IGT + WCST: Offline (pre- and post-last tDCS session) + BIS-11: Offline (pre-tDCS)	A/S	A: F4 + C: F3	35 cm²	2 mA	20 min (3 sessions, 48h intersessions)	IGT + WCST: enhancement in both decision making and cognitive flexibility after tDCS
Xu J, Fregni F, Brody AL, Rahman AS	Randomized sham-controlled single-blind crossover	24 [3 F; mean age 45 ± 7.6 yo; smokers >10 h abstinence; average of 16.4 ± 5.6 cigarettes smoked/day; mean Fagerström score of 5.7 ± 2.0]	Urge to Smoke Scale + Computerized task for testing attention	Offline (pre- and post-tDCS)	A/S	A: F3 + C: contralateral supraorbital area	35 cm²	2 mA	20 min	No significant craving reduction or improvement in attention

Table 2. Detailed information of included studies that assessed tDCS impact on risk taking of healthy and clinical populations.

Authors	Design	Subjects	Task	tDCS parameters						Results
				Online / Offline	Polarity	Electrode position	Surface	Intensity	Duration	
RISK TAKING										
Healthy populations										
Beeli G, Koeneke S, Gasser K, Jancke L	Randomized sham-controlled crossover	24 [all M; all RH; mean age 24.1 ± 2.7 yo]	Driving simulator	Online	A/C	F3 + F4	35 cm²	1 mA	15 min (1 week intersession)	A on F4: prudent behaviors, ↑security distance between cars, ↓speed excess
Cheng GLF, Lee TMC	Randomized sham-controlled within-subjects single-blind	16 [10 F; all RH; mean age 20.9 ± 2.8 yo; mean years of education 14.8 ± 2.1]	Risky-Gains Task (RGT) + Balloon Analogue Risk Task (BART) + Stroop task (baseline only) + Barratt Impulsivity Scale-11 (baseline only)	Online	A/C/S	F3 + F4	35 cm²	2 mA	19 min (48h intersession)	(1) RGT: left C/right A ↓risk-taking vs sham; (2) BART: no significant effect; (3) Risk-taking effect positively correlated with Stroop performance and BIS-AI score
Fecteau S, Knoch D, Fregni F, Sultani N, Boggio P, Pascual-Leone A	Randomized sham-controlled double-blind between-subjects	36 [25 F; mean age 20.3 ± 1.7 yo; 3 LH]	Risk Task	Online	A/C/S	F3 + F4	35 cm²	2 mA	< 15 min	A: F4 + C: F3: ↓influence of reward on choices, ↑accurate choices; faster decision making
Fecteau S, Pascual-Leone A, Zald DH, Liguori P, Théoret H, Boggio PS, Fregni F	Randomized sham-controlled double-blind between-subjects	47 [Study 1: 35 (26 F; mean age 21.0 ± 2.8 yo; 2 LH), study 2: 12 (11 F; mean age 21.7 ± 2.7 yo; 2 LH)]	Balloon Analogue Risk Task (BART) + Stroop task (control condition)	BART: online + Stroop: offline (pre- and post-tDCS)	A/C/S/No stimulation	Study 1: F3 + F4, Study 2: A: F3/F4 + C: contralateral supraorbital area	35 cm²	2 mA	< 15 min	Bilateral tDCS ↓risk taking vs unilateral and sham
Guo H, Zhang Z, Da S, Sheng X, Zhang X	Randomized sham-controlled single-blind between-subjects	58 [37 F; all RH; mean age 20.4 ± 3.0 yo]	Balloon Analogue Risk Task (BART) + Behavioral Inhibition System and Behavioral Approach System scales (BIS/BAS) + Sensation Seeking Scale-5 (SSS-5)	BART: Online + Others: Offline (pre-tDCS, controls)	A/C/S	F3 + return: AF3, F1, F5, FC3	4 cm² (4x1)	1.5 mA	20 min	(1) Subjects earned less money under C vs S stimulation (more conservative, larger effect on the last 10 trials); no contrast when compared to A; no interaction between Group and Time; (2) No difference between groups regarding self-reports

He Q, Chen M, Chen C, Xue G, Feng T, Bechara A	Randomized sham-controlled between-subjects single-blind	41 [all M; mean age 20.7 ± 1.59 yo]	Iowa Gambling Task + Intertemporal Choice Task + Barratt Impulsivity Scale	Offline (post-tDCS)	A/S	G1: A: F3 + C: F5, AF3, FC3 and F1 / G2: A: F4	(4x1) NS	1.5 mA	20 min	(1) Left dlPFC: ↑IGT scores, ↓recency parameter (relied more on the past information and learned faster), ↓delay-discounting rate; (2) BIS: no influence of stimulation
Minati L, Campanhã C, Critchley HD, Boggio PS	Randomized sham-controlled between-subjects	47 [all F; mean ages 21.8 ± 2.5 / 22.3 ± 3.2 / 20.9 ± 1.0 yo; all RH]	Barratt Impulsiveness Scale (BIS) + Gambling task	Online + BIS: offline	A/C/S	F3 + F4	35 cm²	2 mA	20.5 ± 4.1 min	No significant effects
Nejati V, Salehinejad MA, Nitsche MA	Randomized sham-controlled within-subjects single-blind	24 [all M; mean age 26.75 ± 1.89 yo]	Go/No-Go Task + Tower of Hanoi Task + Balloon Analogue Risk Task + Temporal Discounting Task	Online	A/C/S	F3 + Fp2	35 cm²	1.5 mA	20 min (72h intersession)	(1) GNG: A left-dlPFC/C right-OFC ↑No-Go accuracy responses and ↓RT; (2) TOH: both conditions ↓total time of problem solving and A left/C right ↓number of false moves; (3) BART: A left/C right ↓risk taking; (4) TDT: both conditions ↓temporal discounting rate
Ouellet J, McGirr A, Van den Eynde F, Jollant F, Lepage M, Berlim MT	Randomized sham-controlled single-blind between-subjects	45 [29 F; mean age 25.09 ± 7.10 yo; mean years of education 16.89 ± 2.41]	Iowa Gambling Task (IGT) + Balloon Analog Risk Task (BART) + Stroop task + Stop Signal Task (SST)	Offline (pre- and post-tDCS)	A/S	A: Fp1 + C: Fp2	A:35 cm², C: 55.25 cm²	1.5 mA	30 min	(1) IGT: ↑advantage on choices; (2) Stroop: ↓interference scores, with no effect on humor or attentional levels; (3) SSRT not influenced; (4) BART: trend to intervention x time interaction
Pripfl J, Neumann R, Köhler U, Lamm C	Randomized sham-controlled within-subjects	36 [18 smokers (10 F; mean age 22.4 ± 2.5 yo); 18 non-smokers (15 F; 21.0 ± 1.5 yo); all RH; no pathology]	Hot and cold Columbia Card Task (CCT)	Online	A/C/S	A: F1, F3, AF1 + C: F4 / A: F2, F4, AF2 + C: F3	A: 5.3 cm² (total), C: 35 cm²	0.45 mA	15 min (at least 1 week intersession)	(1) Cold: anodal left/cathodal right ↓risk-taking; (2) Hot: anodal right/cathodal left ↓risk-taking for smokers; non-smokers showed ↑risk-taking
Russo R, Twyman P, Cooper NR, Fitzgerald PB, Wallace D	Randomized sham-controlled between-subjects double-blind	198 [Study #1: 117; 68 F; mean age 21.14 ± 2.7 yo; 5 LH / Study #2: 81; 51 F; all RH]	Study #1: Balloon Analogue Risk Task / Study #2: Stroop Task + Balloon Analogue Risk Task	BART: online / Stroop: offline (pre- and post-tDCS)	A/C/S	Study 1: F4 + F3 / Study 2: F4 + F3 or A: F4 / F3 + C: contralateral supraorbital area	Study #1: 25 cm² or 35 cm² / Study #2: 35 cm²	2 mA	Study #1: 30 min / Study #2: 20 min	Study #1: (1) no significant difference between conditions vs sham (right A/left C apparently ↑risk taking); Study #2: (2) no effect observed on Stroop Task or BART; (3) Combined data from both studies showed no significant differences between conditions
Ye H, Chen S, Huang D, Wang S, Jia Y, Luo J	Randomized sham-controlled between-subjects	60 [36 F; mean age 21.3 yo; all RH]	Menu of paired lottery choices + Self-assessment of risk preference questionnaire	Offline (pre- and post-tDCS) + Questionnaire: post-tDCS	A/C/S	F4 + F3	35 cm²	2 mA	15 min	(1) Right A/left C ↓risk aversion and ↑choice for risky options vs sham; (2) No significant difference between the two groups receiving active stimulation; (3) Self-assessment of risk preference significantly associated with number of safe options

Ye H, Chen S, Huang D, Wang S, Luo J	Randomized sham-controlled between-subjects	60 [35 F; mean age 21.4 yo]	Risk-measurement table	Offline (pre-tDCS) and online (last 3 stimulation min)	A/C/S	F4 + F3	35 cm²	2 mA	18 min	↑Risk aversion after right A/left C vs sham, while left A/right C showed no difference vs sham
Ye H, Huang D, Wang S, Zheng H, Luo J, Chen S	Randomized sham-controlled between-subjects single-blind	100 [64 F; mean age 21.3 yo; all RH]	Risk-measurement table + Self-assessment of risk preference questionnaire	Offline (pre-tDCS) and online (last 3 stimulation min) + Questionnaire: post-tDCS	A/C/S	A: F4 / F3 + C: Pz or C: F4 / F3 + A: Pz	35 cm²	2 mA	18 min	(1) Right A: ↓risk aversion in the gain frame and ↑risk aversion in the loss frame; (2) Left C: ↓risk aversion in the gain frame; (3) No significant difference in self-assessment of risk preference between conditions
Clinical populations										
Boggio PS, Zaghi S, Villani AB, Fecteau S, Pascual-Leone A, Fregni F	Randomized sham-controlled double-blind between-subjects	25 [10 F; all RH; mean age 22.8 ± 2.6 yo; history of marijuana use 5.8 ± 2.7 years; frequency 5.5 ± 1.9 episodes/week]	Risk Task + Self rated craving	Online + Offline (pre- and post-tDCS)	A/C/S	F3 + F4	35 cm²	2 mA	15 min	(1) Active stimulation (A/C) ↑high-risk prospects vs sham; (2) ↓Craving after right A/left C
Fecteau S, Agosta S, Hone-Blanchet A, Fregni F, Boggio P, Ciraulo D, Pascual-Leone A	Randomized sham-controlled crossover blind at four levels (group allocator, subjects, tDCS provider, outcome assessor)	12 [7 F; mean age 36.3 yo; smokers in contemplator stage]	Smoking intake + Questionnaire of Smoking Urges + Ultimatum Game + Risk Task	Offline (pre- and post-regimen)	A/S	A: F4 + C: F3	35 cm²	2 mA	30 min (5 sessions, 24h intersessions)	(1) ↓Numbers of cigarettes; (2) ↓Desire to smoke scale; (3) Ultimatum Game: ↑rejection on offers when reward was cigarettes (reward sensitive effect); (4) Risk Task: no significant effect
Gorini A, Lucchiari C, Russell-Edu W, Pravettoni G	Randomized sham-controlled within-subjects single-blind	36 [8 F; mean age 38.4 ± 7.5 yo; 18 dependent cocaine users and 18 controls, non-abusers]	Balloon Analogue Risk Task + Game of Dice Task + Barratt impulsiveness scale-11	Offline (pre- and post-tDCS) + BIS-11: pre-tDCS	A/C/S	F4 + F3	32 cm²	1.5 mA	20 min (48h intersession)	(1) No significant correlation between BIS-11 score and task performance; (2) BART:↓risk-taking in both stimulation conditions; (3) GDT: right A ↑conservative bets (safe behavior) and left A ↑risky choices in patient group, while only right A ↑safe bets in control group
Soyata AZ, Aksu S, Woods AJ, İşçen P, Saçar KT, Karamürsel S	Randomized sham-controlled triple-blind parallel	20 [all M; all RH; mean age 37.2 ± 10.3 yo; gambling disorder diagnosis]	Iowa Gambling Task (IGT) + Wisconsin Card Sorting Test (WCST)	IGT + WCST: Offline (pre- and post-last tDCS session) + BIS-11: Offline (pre-tDCS)	A/S	A: F4 + C: F3	35 cm²	2 mA	20 min (3 sessions, 48h intersessions)	IGT + WCST: enhancement in both decision making and cognitive flexibility after tDCS

Table 3. Detailed information of included studies that assessed tDCS impact on planning of healthy and clinical populations.

Authors	Design	Subjects	Task	tDCS parameters						Results
				Online / Offline	Polarity	Electrode position	Surface	Intensity	Duration	
PLANNING										
Healthy populations										
Dockery CA, Hueckel-Weng R, Birbaumer N, Plewnia C	Randomized sham-controlled whithin-subjects single-blind	24 [19 F; mean age 24 ± 3.16 yo; average years of education 16.8 ± 2.63]	Tower of London Task	Online + offline (post-tDCS)	A/C/S	F3 + above right orbit	35 cm²	1 mA	15 min (3 sessions, 1 week intersession)	(1) C → A: ↑planning ability (A: learning phase dependent); (2) Effect persistence for 6 or 12 months
Heinze K, Ruh N, Nitschke K, Reis J, Fritsch B, Unterrainer JM, Rahm B, Weiller C, Kaller CP	Pseudo-randomized sham-controlled between-subjects	45 [all RH; range 19-28 yo]	Tower of London Task	Online and offline (post-tDCS)	A/C/S	F4 + F3	25 cm²	1 mA	15 min	(1) Left C/right A: ↓initial thinking time and last gaze before movement execution (eye-tracking); (2) Effects did not sustain post-tDCS
Nejati V, Salehinejad MA, Nitsche MA	Randomized sham-controlled within-subjects single-blind	24 [all M; mean age 26.75 ± 1.89 yo]	Go/No-Go Task + Tower of Hanoi Task + Balloon Analogue Risk Task + Temporal Discounting Task	Online	A/C/S	F3 + Fp2	35 cm²	1.5 mA	20 min (72h intersession)	(1) GNG: A left-dlPFC/C right-OFC ↑No-Go accuracy responses and ↓RT; (2) TOH: both conditions ↓total time of problem solving and A left/C right ↓number of false moves; (3) BART: A left/C right ↓risk taking; (4) TDT: both conditions ↓temporal discounting rate

Table 4. Detailed information of included studies that assessed tDCS impact on delay discounting of healthy and clinical populations.

Authors	Design	Subjects	Task	tDCS parameters						Results
				Online / Offline	Polarity	Electrode position	Surface	Intensity	Duration	
DELAY DISCOUNTING										
Healthy populations										
He Q, Chen M, Chen C, Xue G, Feng T, Bechara A	Randomized sham-controlled between-subjects single-blind	41 [all M; mean age 20.7 ± 1.59 yo]	Iowa Gambling Task + Intertemporal Choice Task + Barratt Impulsivity Scale	Offline (post-tDCS)	A/S	G1: A: F3 + C: F5, AF3, FC3 and F1 / G2: A: F4	(4x1) NS	1.5 mA	20 min	(1) Left dlPFC: ↑IGT scores, ↓recency parameter (relied more on the past information and learned faster), ↓delay-discounting rate; (2) BIS: no influence of stimulation
Hecht D, Walsh V, Lavidor M	Randomized sham-controlled within-subjects	14 [7 F; mean age 26.7 ± 4.7 yo]	Delay discounting task	Online	A/C/S	F3 + F4	9 cm²	1.6 mA	20 min (~47h intersession)	A F3 + C F4: ↑tendency to immediate choices
Kekic M, McClelland J, Campbell I, Nestler S, Rubia K, David AS, Schmidt U	Randomized sham-controlled within-subjects double-blind	17 [all F; mean age 26.41 ± 8.3 yo; mean BMI 23.81 + 2.6 kg/m²; 29.4% overweight]	Temporal Discounting (TD) task + Food craving questionnaire	Offline (pre- and post-tDCS)	A/S	A: F4 + C: F3	25 cm²	2 mA	20 min (48h intersession)	(1) ↓Craving for sweet foods; (2) No significant effect on TD; subjects with ↑intertemporal decision-making abilities ↑susceptible to anti-craving effects post-tDCS
Maréchal MA, Cohn A, Ugazio G, Ruff CC	Randomized sham-controlled between-subjects double-blind	145 [72 F; 23 ± 4 yo; all RH]	Delay discounting task	Online	A/C/S	rDLPFC, return over the vertex	35 cm², return 100 cm²	1.5 mA	30 min	No significant tDCS influence

Nejati V, Salehinejad MA, Nitsche MA	Randomized sham-controlled within-subjects single-blind	24 [all M; mean age 26.75 ± 1.89 yo]	Go/No-Go Task + Tower of Hanoi Task + Balloon Analogue Risk Task + Temporal Discounting Task	Online	A/C/S	F3 + Fp2	35 cm²	1.5 mA	20 min (72h intersession)	(1) GNG: A left-dlPFC/C right-OFC ↑No-Go accuracy responses and ↓RT; (2) TOH: both conditions ↓total time of problem solving and A left/C right ↓number of false moves; (3) BART: A left/C right ↓risk taking; (4) TDT: both conditions ↓temporal discounting rate
Shen B, Yin Y, Wang J, Zhou X, McClure SM, Li J	Randomized sham-controlled within-subjects	117 [54 F; all RH]	Intertemporal choice (ITC) task	Online	A/C/S	Study 1 (tDCS): F3 + F4; Study 2 (HD-tDCS): F3 / F4 + return C3, FT7, Fp1, Fz / C4, FT8, Fp2, Fz	tDCS: 35 cm² / HD-tDCS: ~4 cm² (4x1 disposition)	2 mA	20 min (24h intersession)	(1) tDCS: no significant effects; (2) HD-tDCS: A to F3 ↓impulsivity, C to F3 ↑impulsivity
Clinical populations										
Kekic M, McClelland J, Bartholdy S, Boysen E, Musiat P, Dalton B, Tiza M, David AS, Campbell IC, Schmidt U	Randomized sham-controlled whithin-subjects double-blind	39 [37 F; mean age 25.85 ± 6.62 yo; mean BMI 21.65 kg/m²; 87.2% RH; bulimia nervosa diagnosis]	Urge to binge-eat Visual Analogue Scale + Temporal Discounting Task	Offline (pre- and post-tDCS)	A/C/S	F4 + F3	25 cm²	2 mA	20 min (48h intersession)	Both configurations suppressed urge to binge-eat and ↑self-regulatory control during TD task

Table 5. Detailed information of included studies that assessed tDCS impact on craving of healthy and clinical populations.

Authors	Design	Subjects	Task	tDCS parameters						Results
				Online / Offline	Polarity	Electrode position	Surface	Intensity	Duration	
CRAVING										
Healthy populations										
Fregni F, Orsati F, Pedrosa W, Fecteau S, Tome FAM, Nitsche MA, Mecca T, Macedo EC, Pascual-Leone A, Boggio PS	Randomized sham-controlled double-blind whithin-subjects	23 [21 F; mean age 23.7 ± 7.2 yo]	Visual Analogue Scale	Offline (pre- and post-tDCS)	A/C/S	F4 + F3	35 cm²	2 mA	20 min (48h intersession)	↓Craving only after anode right/cathode left stimulation
Georgii C, Goldhofer P, Meule A, Richard A, Blechert J	Randomized sham-controlled double-blind crossover	42 [only F; average age 22.02 yo; average BMI 22.6 kg/m²: 4 underweight, 31 normal weight, 4 overweight, 2 obese]	Barratt Impulsiveness Scale – short form (BIS-15) + Food Craving Questionnaire-State + Food choice task	BIS: Offline (pre-tDCS) + Others: Offline (pre- and post-tDCS)	A/S	A: F4 + C: F3	35 cm²	1 mA	20 min (1 week intersession)	No main effects of tDCS condition vs impulsivity vs momentary food craving / type of foods / number of choices for high caloric foods / calorie intake
Goldman RL, Borckardt JJ, Frohman HA, O'Neil PM, Madan A, Campbell LK, Budak A, George MS	Randomized sham-controlled crossover	19 [13 F; mean age 32.47 ± 10.85 yo; mean BMI 27.25 kg/m²]	International Affective Picture System (IAPS) + Visual Analogue Scale for craving	Offline (pre-tDCS) + online	A/S	A: F4 + C: F3	25 cm²	2 mA	20 min	(1) ↓Craving for sweet food and carbohydrate food; (2) ↓Inability to resist sweet food
Kekic M, McClelland J, Campbell I, Nestler S, Rubia K, David AS, Schmidt U	Randomized sham-controlled within-subjects double-blind	17 [all F; mean age 26.41 ± 8.3 yo; mean BMI 23.81 + 2.6 kg/m²; 29.4% overweight]	Temporal Discounting (TD) task + Food Craving Questionnaire-State	Offline (pre- and post-tDCS)	A/S	A: F4 + C: F3	25 cm²	2 mA	20 min (48h intersession)	(1) ↓Craving for sweet foods; (2)No significant effect on TD; subjects with ↑intertemporal decision-making abilities ↑susceptible to anti-craving effects post-tDCS
Lapenta OM, Sierve KD, de Macedo EC, Fregni F, Boggio PS	Randomized sham-controlled double-blind crossover	9 [all F; mean age 23.4 ± 2 yo; normal range for BMI]	Go/No-go Task + Visual Analogue Scale for the urge to eat	VAS: online and offline (pre- and post-tDCS) + GNG: offline (post-tDCS)	A/S	A: F4 + C: F3	35 cm²	2 mA	20 min	(1) GNG: no main effects of stimulation; (2) ↓Craving post-stimulation
Ljubisavljevic M, Maxood K, Bjekic J, Oommen J, Nagelkerke N	Randomized sham-controlled double-blind between-subjects	27 [all RH; +18 yo; BMI ≥18.5]	Food Craving Questionnaire-State + Food Craving Questionnaire-Trait + Food Craving Inventory	Offline (pre- and 1 day, 5 days and 30 days post-first session)	A/S	A: F4 + C: left forehead	35 cm²	2 mA	20 min (5 sessions, 24h intersessions)	(1) ↓Craving (sweet, fast-food and fat) after a single session; (2) Persistent effects (after 30 days)
Clinical populations										

Batista EK, Klauss J, Fregni F, Nitsche MA, Nakamura-Palacios EM	Randomized sham-controlled double-blind between-subjects	36 [all M; average 30.4 yo; crack-cocaine dependence; 83.3% also tobacco smokers]	Obssessive Compulsive Cocaine Scale	Offline (pre- and post-tDCS, up to 4 weeks after first session)	A/S	A: F4 + C: F3	35 cm²	2 mA	20 min (5 sessions with 24h intersessions)	Craving scores decreased linearly from baseline (week before treatment) to the week after treatment only in the tDCS group
Boggio PS, Liguori P, Sultani N, Rezende L, Fecteau S, Fregni F	Randomized sham-controlled double-blind between-subjects	27 [15 F; mean age 26.3 yo; smokers ≥10 cigarettes/day for at least 1 year]	Visual Analogue Scale	Offline (pre-tDCS, on days 1 and 5, and post-tDCS)	A/S	A: F3 + C: F4	A: 35 cm² + C: 100 cm²	2 mA	20 min (5 sessions, 24h intersessions)	(1) ↓Craving after active stimulation; (2) ↓Cue-induced craving increased after each session, except for the last day of stimulation
Boggio PS, Sultani N, Fecteau S, Merabet L, Mecca T, Pascual-Leone A, Basaglia A, Fregni F	Randomized sham-controlled double-blind whithin-subjects	13 [2 F; mean age 41.3 yo; alcohol dependence diagnosis]	Alcohol Urge Questionnaire	Offline (pre- and post-tDCS)	A/C/S	F3 + F4	35 cm²	2 mA	20 min (48h intersession)	Both A and C ↓craving vs sham
Boggio PS, Zaghi S, Villani AB, Fecteau S, Pascual-Leone A, Fregni F	Randomized sham-controlled double-blind between-subjects	25 [10 F; all RH; mean age 22.8 ± 2.6 yo; history of marijuana use 5.8 ± 2.7 years; frequency 5.5 ± 1.9 episodes/week]	Risk Task + Self rated craving	Online + Offline (pre- and post-tDCS)	A/C/S	F3 + F4	35 cm²	2 mA	15 min	(1) Active stimulation (A/C) ↑high-risk prospects vs sham; (2) ↓Craving after right A/left C
Burgess EE, Sylvester MD, Morse KE, Amthor FR, Mrug S, Lokken KL, Osborn MK, Soleymani T, Boggiano MM	Randomized sham-controlled crossover	30 [20 F; BED or subBED; mean BMI 36.1 kg/m2]	Food Photo Craving Test + Eating Test + Binge Eating Scale	Offline (pre- and post-tDCS)	A/S	A: F4 + C: F3	25 cm²	2 mA	20 min	(1) ↓Craving for desserts (more in men than women), savory proteins and all-food category (also more in men); (2) No reduced intake of any food type; (3) ↓Desire to binge-eat 5-6h post-session in men only
Conti CL, Moscon JA, Fregni F, Nitsche MA, Nakamura-Palacios EM	Randomized sham-controlled between-subjects	13 [2 F; 18-60 yo; crack-cocaine dependence diagnosis; up to 31 days of abstinence]	Brief Cocaine Craving Questionnaire	Offline (pre- and post-one and five tDCS sessions)	A/S	A: F4 + C: F3	35 cm²	2 mA	20 min (5 sessions, 48h intersession)	(1) Only 8 subjects completed all sessions; (2) No significant changes on craving
den Uyl TE, Gladwin TE, Lindenmeyer J, Wiers RW	Randomized sham-controlled double-blind between-subjects	83 [23 F; mean age 48.6 yo; alcohol-dependent patients]	Alcohol Attentional Bias Modification Task + Penn Alcohol Craving Scale	ABM: Online + PACS: Offline (pre- and post-tDCS, 1 to 7 days after last session)	A/S	A: F3 + C: F4	A: 35 cm² + C: 100 cm²	2 mA	20 min (4 sessions within 1 week)	(1) ABM: no beneficial effects of tDCS on changing attentional bias were found; (2) PACS extremely low reported craving; ↓ from preassessment to postassessment

den Uyl TE, Gladwin TE, Rinck M, Lindenmeyer J, Wiers RW	Randomized sham-controlled double-blind between-subjects	91 [30 F; mean age 47 ± 8.8 yo; alcohol-dependents]	Pennsylvania Alcohol Craving Questionnaire	Offline (pre- and post-first tDCS session)	A/S	A: F3 + C: F4	A: 35 cm² + C: 100 cm² (~ unilateral)	2 mA	20 min (4 sessions, 24h intersessions, with or without Cognitive Bias Modification)	No main effects of stimulation condition
den Uyl TE, Gladwin TE, Wiers RW	Randomized sham-controlled double-blind between-subjects	41 [26 F; mean age 21.7 ± 3 yo; all RH; heavy drinkers; 60% occasional drug-users]	Alcohol approach and avoidance questionnaire	Offline (pre- and post-tDCS)	A/S	A: F3(dlPFC) / crossing point between F7 and Cz and Fz and T3 (rIFG) + C: contralateral supraorbital region	35 cm²	1 mA	10 min	(1) ↓Craving after dlPFC stimulation vs sham; (2) No difference between IFG stimulation and sham
den Uyl TE, Gladwin TE, Wiers RW	Randomized sham-controlled double-blind between-subjects	78 [51 F; mean age 21.8 ± 3.2 yo; hazardous drinkers]	Cue Craving Task	Offline (pre- and post-tDCS)	A/S	A: F3 + C: contralateral supraorbital area	35 cm²	1 mA	15 min (3 sessions, 48h intersessions, with or without Cognitive Bias Modification)	Craving decreased over time, but there was no interaction with tDCS or CBM
Falcone M, Bernardo L, Ashare RL, Hamilton R, Faseyitan O, McKee SA, Loughead J, Lerman C	Randomized sham-controlled double-blind crossover	28 [13 F; mean age 42.1 ± 11.2 yo; average 15.2 ± 4.4 cigarettes/day]	Latency to smoke (in minutes) + number of cigarettes smoked during resist and *ad libitum* periods	Offline (post-tDCS)	A/S	A: F3 + C: contralateral supraorbital area	25 cm²	1 mA	20 min	(1) ↑Latency to smoke; (2) ↓Total number of cigarettes smoked
Fecteau S, Agosta S, Hone-Blanchet A, Fregni F, Boggio P, Ciraulo D, Pascual-Leone A	Randomized sham-controlled crossover blind at four levels (group allocator, subjects, tDCS provider, outcome assessor)	12 [7 F; mean age 36.3 yo; smokers in contemplator stage]	Smoking intake + Questionnaire of Smoking Urges + Ultimatum Game + Risk Task	Offline (pre- and post-regimen)	A/S	A: F4 + C: F3	35 cm²	2 mA	30 min (5 sessions, 24h intersessions)	(1) ↓Numbers of cigarettes; (2) ↓Desire to smoke scale; (3) Ultimatum Game: ↑rejection on offers when reward was cigarettes (reward sensitive effect); (4) Risk Task: no significant effect

Fregni F, Liguori P, Fecteau S, Nitsche MA, Pascual-Leone A, Boggio PS	Randomized sham-controlled double-blind whithin-subjects	24 [11 F; mean age 24.8 ± 7.6 yo; mean of 18.5 cigarettes/day]	Visual Analogue Scale	Offline (pre- and post-tDCS)	A/C/S	F3 + F4	A: 35 cm² / C: 100 cm²	2 mA	20 min (48h intersession)	Active stimulation ↓general craving and ↓cue-elicited craving
Kekic M, McClelland J, Bartholdy S, Boysen E, Musiat P, Dalton B, Tiza M, David AS, Campbell IC, Schmidt U	Randomized sham-controlled double-blind whithin-subjects	39 [37 F; mean age 25.85 ± 6.62 yo; mean BMI 21.65 kg/m²; 87.2% RH; bulimia nervosa diagnosis]	Urge to binge-eat Visual Analogue Scale + Temporal Discounting Task	Offline (pre- and post-tDCS)	A/C/S	F4 + F3	25 cm²	2 mA	20 min (48h intersession)	Both configurations suppressed urge to binge-eat and ↑self-regulatory control during TD task
Klauss J, Anders QS, Felippe LV, Ferreira LVB, Cruz MA, Nitsche MA, Nakamura-Palacios EM	Randomized sham-controlled double-blind parallel	35 [6 F; mean age 35 ± 8.7 yo; admitted to the hospitals for crack-cocaine use disorder (regular treatment for 30 days or global clinical stabilization); average 19.1 rocks/day; about 33 days of abstinence; 66.7% also tobacco smokers]	Obsessive-Compulsive Cocaine Scale (OCCS)	Offline (1 week pre-tDCS - baseline; once a week during 3 week treatment sessions; and 1 week after last session)	A/S	A: F4 + C: F3	35 cm²	2 mA	20 min (10 sessions, 48h intersessions)	No significant effect when comparing active vs S stimulation
Klauss J, Anders QS, Felippe LV, Nitsche MA, Nakamura-Palacios EM	Randomized sham-controlled double-blind parallel	45 [8 F; mean age 44.9 ± 11.1 yo; alcohol dependents; average 17.9 drinks/day; about 33 days of abstinence; 51.5% also tabacco smokers]	Brief Obsessive Compulsive Drinking Scale (OCDS)	Offline (1 week pre-tDCS, once a week during 3 weeks treatment, and 1 week after last session)	A/S	A: F4 + C: F3	35 cm²	2 mA	20 min (10 sessions, 48h intersessions)	A vs S: significant ↓ craving between groups and in the 5 points in time (↓ scores on 3rd, 4th and 5th measurements vs baseline, and ↓ scores on 4th and 5th vs 2nd measurement: active sessions only)
Klauss J, Penido Pinheiro LC, Silva Merlo BL, de Almeida Correia Santos G, Fregni F, Nitsche MA, Miyuki Nakamura-Palacios E	Randomized sham-controlled single-blind between-subjects	33 [1 F; mean age 44.8 ± 8.3 yo; alcohol dependents; average of 17.3 ± 15.3 drinks/day]	Obsessive Compulsive Drinking Scale	Offline (pre- and post-tDCS)	A/S	A: F4 + C: F3	35 cm²	2 mA	26 min (daily sessions with 20 min no stimulation interval - 13:20:13 schedule - for 5 consecutive days)	No differences between groups when comparing before and after treatment
Kroczek AM, Häußinger FB, Rohe T, Schneider S, Plewnia C, Batra A, Fallgatter AJ, Ehlis A-C	Randomized sham-controlled double-blind between-subjects	25 [15 F; smokers; average amount of cigarettes smoked/week: verum group: 34 ± 45, placebo group: 35 ± 37]	Verbal rated craving every 2 min	Online	A/S	A: F3 + C: Fp2	35 cm²	2 mA	15 min	No main effects of stimulation condition

Mondino M, Luck D, Grot S, Januel D, Suaud-Chagny M-F, Poulet E, Brunelin J	Randomized sham-controlled double-blind parallel	29 [20 F; mean age 41.2 ± 9.1 yo (active group), 40.8 ± 9.4 yo (sham group); tobacco smokers, 10-25 cigarettes consumption/day, score ≥5 at the Fargeström Test for Nicotine Dependence, wish to quit smoking]	5-item questionnaire of smoking urge	Offline (pre- and post-each tDCS session)	A/S	A: between F4 and Fp2 (right dlPFC) + C: between O1 and T5 (left occipital region)	A: 35 cm² + C: 100 cm²	2 mA	20 min (10 sessions: 2/day, minimum 2h intersessions, 5 consecutive days)	↓Craving with significant effect of session (especially after the first tDCS session) and significant effect of active stimulation vs S; no cumulative effect
Nakamura-Palacios EM, de Almeida Benevides MC, da Penha Zago-Gomes M, de Oliveira RWD, de Vasconcellos VF, de Castro LNP, da Silva MC, Ramos PA, Fregni F	Randomized sham-controlled crossover	49 [4 F; mean age 48.8 ± 8.9 yo; alcohol-dependence diagnosis; Lesch's type I (16), II (7), III (14) and IV (12)]	Go/No-Go task [FAB] + Obsessive Compulsive Drinking Scale	Offline (pre- and post-tDCS)	A/S	A: F3 + C: contralateral supradeltoid area	35 cm²	1 mA	10 min	(1) Significant ↑FAB scores after active tDCS for Lesch's type IV group only; (2) No significant effects on craving
Nakamura-Palacios EM, Lopes IBC, Souza RA, Klauss J, Batista EK, Conti CL, Moscon JA, de Souza RSM	Randomized sham-controlled between-subjects	14 [all M; crack-cocaine dependents]	Obsessive Compulsive Cocaine Use Scale	Offline (pre- and post-tDCS)	A/S	A: F4 + C: F3	35 cm²	2 mA	20 min or 13 min + 20 min interval + 13 min (5 sessions, 24-48h intersession)	↓Craving
Pripfl J, Lamm C	Randomized sham-controlled whithin-subjects	17 [11 F; tobacco smokers; mean age 22.2 ± 2.0 yo; mean score of 2.3 ± 1.4 in the Fagerström Test for Nicotine Dependence]	Cue induced Craving	Online	A/S	A: F1, F3 and AF1 / F2, F4 and AF2 + C: F4 / F3	A: 5.3 cm² + C: 35 cm²	0.45 mA	15 min (at least 1 week intersessions)	No significant effects of stimulation condition on craving
Shahbabaie A, Ebrahimpoor M, Hariri A, Nitsche MA, Hatami J, Fatemizadeh E, Oghabian MA, Ekhtiari H	Randomized sham-controlled double-blind crossover	15 [all M; all RH; mean age 31.33 ± 1.4 yo; methamphetamine use disorder diagnosis, with at least 1 week abstinence]	Subjective craving rate	Offline (pre- and post-tDCS)	A/S	A: F4 + C: F3	35 cm²	2 mA	20 min (1 week intersessions)	Significant ↓ craving after active vs S
Shahbabaie A, Golesorkhi M, Zamanian B, Ebrahimpoor M, Keshvari F, Nejati V, Fregni F, Ekhtiari H	Randomized sham-controlled double-blind crossover	30 [all M; mean age 29.9 yo; all RH; at least 12 months of methamphetamine dependence]	Computerized cue-induced craving assessment task + Visual Analog Scale (craving)	Cue-induced: online / At rest: offline (pre- and post-tDCS)	A/S	A: F4 + C: contralateral supraorbital area	35 cm²	2 mA	20 min	(1) ↓Craving at rest from pre- to during-tDCS; (2) Active stimulation over right dlPFC induced ↑craving ratings during cue exposure vs sham
Smith RC, Boules S, Mattiuz S, Youssef M, Tobe RH, Sershen H, Lajtha A, Nolan K, Amiaz R, Davis JM	Randomized sham-controlled double-blind between-subjects	33 [9 F; mean age: active group: 46.76 ± 11.06, sham: 44.88 ± 9.19 yo; diagnosis of schizophrenia or schizoaffective psychosis; all regular cigarette smokers]	Questionnaire of smoking urges + Visual Analogue Scale (craving)	Offline (pre- and post-tDCS)	A/S	A: F3 + C: Fp2	2 x 5.08 cm²	2 mA	20 min (5 sessions, 24h intersessions)	No differences in the effects of active vs sham

Wang Y, Shen Y, Cao X, Shan C, Pan J, He H, Ma Y, Yuan T-F	Randomized sham-controlled double-blind between-subjects	20 [all M; mean age 39.8 ± 1.8 yo; heroin use history; abstinent for at least 1.5-2 years]	Self-rated (cue-induced) craving score	Offline (pre- and post-tDCS)	C/S	C: T4, T3 + A: O1, O2	35 cm²	1.5 mA	20 min	↓Heroin craving score after active stimulation vs sham
Wietschorke K, Lippold J, Jacob C, Polak T, Herrmann MJ	Randomized sham-controlled double-blind between-subjects	30 [11 F; 18-60 yo; all RH; alcohol dependence with finished detoxification]	Visual Analogue Scale (stimulus-induced craving)	Online	A/S	A: F4 + C: F3	35 cm²	1 mA	20 min	↓Subjective craving (for tendencies "intention to drink" and "desire")
Xu J, Fregni F, Brody AL, Rahman AS	Randomized sham-controlled single-blind crossover	24 [3 F; mean age 45 ± 7.6 yo; smokers >10 h abstinence; average of 16.4 ± 5.6 cigarettes smoked/day; mean Fagerström score of 5.7 ± 2.0]	Urge to Smoke Scale + computerized task for testing attention	Offline (pre- and post-tDCS)	A/S	A: F3 + C: contralateral supraorbital area	35 cm²	2 mA	20 min	No significant craving reduction or improvement in attention
Yang L-Z, Shi B, Li H, Zhang W, Liu Y, Wang H, Zhou Y, Wang Y, Lv W, Ji X, Hudak J, Zhou Y, Fallgatter AJ, Zhang X	Randomized sham-controlled single-blind whithin-subjects	32 [all M; mean age 26.68 ± 6.28 yo; all RH; tobacco smokers; average number of cigarettes/day 14.41 ± 4.36; average years of smoking 8.11 ± 7.02; average Fagerström Test for Nicotine Dependence score 5.03 ± 1.4]	Self-reported (cue-induced) craving by Visual Analogue Scale	Offline (post-tDCS)	A/S	A: F3 + C: F4	A: 35 cm² + C: 100 cm²	1 mA	30 min	↓Cue-induced craving increase after real stimulation

Table 6. Impulsivity dimensions (tasks) and tested cortical targets (with number of studies and samples) classified according to tDCS outcome (positive, negative or no effect) on healthy participants.

Task	tDCS outcome *								
	Positive effect	Trials (n)	Subjects (n)	**Negative effect**	Trials (n)	Subjects (n)	**No effect**	Trials (n)	Subjects (n)
RESPONSE INHIBITION									
Stop Signal Task	right IFG (A)	5	115 + 26 + 22 + 22 + 22	right IFG (C)	1	22	OFC (B)	1	45
	left dlPFC (A + high-tempo music)	1	73	sMFC (C)	1	18			
	right dlPFC (A)	1	56	right IFG (A)	1	14			
	right IFC (A)	1	46						
	pre-SMA (A)	4	40 + 40 + 31 + 28						
Go/No-Go Task	right IFG (A)	1	35	left dlPFC (C)	2	41 + 35	IFG (B, AR/CL)	2	64 + 16
	left dlPFC (A + C right OFC)	1	24				left lPFC (A/C)	1	59
	IFG (AR/CL)	1	23				left dlPFC (A)	1	46
							right IFG (A)	1	31
							right dlPFC (A/C)	1	18
							dlPFC (AR/CL)	1	9
Stroop Task	OFC (AL/CR)	1	45				dlPFC (B)	1	81
	dlPFC (AL/CR)	1	28						
Approach-Avoidance Task	dlPFC (AR/CL)	1	202						
AX-CPT	right IFJ (A) and right dlPFC (C)	1	164						
SNARC task	left dlPFC (C)	1	72						
Cognitive Reflection Test				left dlPFC (C)	1	39			
Stimulus-response compatibility task	pre-SMA (C)	1	24						
Hayling Task	dlPFC (AL/CR)	1	20						
Prepotent response inhibition task	right IFG (A)	1	16						
Choice Reaction Time							IFG (AR/CL)	1	16
RISK TAKING									
Balloon Analogue Risk Task	left dlPFC (C)	1	58				dlPFC (B)	3	117 + 81 + 16

	dlPFC (B)	1	47				left / right dlPFC (A)	1	81
	left dlPFC (A + C right OFC)	1	24				OFC (AL/CR)	1	45
Iowa Gambling Task	left OFC (A)	1	45						
	left dlPFC (A)	1	41						
Risk-measurement table	right dlPFC (A)	1	100	right dlPFC (A)	1	100			
	dlPFC (AR/CL)	1	60	left dlPFC (C)	1	100			
Menu of paired lottery choices				dlPFC (AR/CL)	1	60			
Gambling Task							dlPFC (B)	1	47
Risk Task	dlPFC (AR/CL)	1	36						
Hot and cold Columbia Card Task	dlPFC (AL/CR)	1	36	dlPFC (AR/CL)	1	36			
Driving simulator	dlPFC (AR/CL)	1	24						
Risky-Gains Task	dlPFC (AR/CL)	1	16						
PLANNING									
Tower of London Task	dlPFC (AR/CL)	1	45						
	left dlPFC	1	24						
Tower of Hanoi Task	left dlPFC (A + C right OFC)	1	24						
DELAY DISCOUNTING									
Delay Discounting Task				dlPFC (AL/CR)	1	14	right dlPFC (A/C)	1	145
Intertemporal Choice Task	left dlPFC (A)	2	117 + 41	left dlPFC (C)	1	117	dlPFC (B)	1	117
Temporal Discounting Task	left dlPFC (A/C + return right OFC)	1	24				dlPFC (AR/CL)	1	17
CRAVING									
Food	right dlPFC (A)	1	27				dlPFC (AR/CL)	1	42
	dlPFC (AR/CL)	4	23 + 19 + 17 + 9						

* Electrode polarity over the targeted area is detailed between parentheses. The "/" character indicates a bilateral disposition over hemispheres.

A anode; B bilateral (meaning both anode right/cathode left and anode left/cathode right montages were tested); C cathode; dlPFC dorsolateral pre-frontal cortex; IFC inferior frontal cortex; IFG inferior frontal gyrus; IFJ inferior frontal junction; lPFC lateral prefrontal cortex; L left; OFC orbitofrontal cortex; pre-SMA pre-supplementary motor area; R right; sMFC superior medial frontal cortex.

Table 7. Impulsivity dimensions (tasks) and tested cortical targets (with number of studies and samples) classified according to tDCS outcome (positive, negative or no effect) on clinical populations.

Task	Pathology	tDCS outcome *								
		Positive effect	Trials (n)	Subjects (n)	**Negative effect**	Trials (n)	Subjects (n)	**No effect**	Trials (n)	Subjects (n)
RESPONSE INHIBITION										
Stop Signal Task	ADHD							left dlPFC (A)	1	37
Conners' Continuous Performance Task	ADHD	left dlPFC (A)	1	37						
Go/No-Go Task	ADHD							dlPFC (AL/CR)	1	60
Affective Go/No-Go Task	Depression	left dlPFC (A)	1	26						
Go/No-Go Task (FAB)	Alcohol-dependence	left dlPFC (A)	2	49 + 13						
Alcohol Attentional Bias Modification Task	Alcohol-dependence							dlPFC (AL/CR)	1	83
Pictorial Probe Detection Task	Methamphetamine use	dlPFC (AL or AL/CR)	1	90						
Computerized task for testing attention	Tobacco-dependence							left dlPFC (A or C)	1	24
Wisconsin Card Sorting Test	Gambling disorder	dlPFC (AR/CL)	1	20						
RISK TAKING										
Balloon Analogue Risk Task	Cocaine-dependence	dlPFC (B)	1	36						
Game of Dice Task	Cocaine-dependence	dlPFC (AR/CL)	1	36	dlPFC (AL/CR)	1	36			
Risk Task	Marijuana use				dlPFC (B)	1	25			
Risk Task	Tobacco-dependence							dlPFC (AR/CL)	1	12
Iowa Gambling Task	Gambling disorder	dlPFC (AR/CL)	1	20						
DELAY DISCOUNTING										
Temporal Discounting Task	Bulimia nervosa	dlPFC (B)	1	39						
CRAVING										
Food	Bulimia nervosa	dlPFC (AR/CL)	1	39						
	Binge eating disorder	dlPFC (B)	1	30						
Alcohol	Alcohol-dependence	left dlPFC (A)	2	83 + 41				left dlPFC (A)	3	91 + 78 + 49
		dlPFC (AR/CL)	2	45 + 30				dlPFC (AR/CL)	1	33
		dlPFC (B)	1	13						
Tobacco	Tobacco-dependence in schizophrenia							left dlPFC (A + C right OFC)	1	33
	Tobacco-dependence	left dlPFC (A)	4	32 + 28 + 27 + 24				left dlPFC (A + C right OFC)	1	25

		right dlPFC (A)	1	29				left dlPFC (A)	1	24
		dlPFC (AR/CL)	1	12				left/right dlPFC (A/C)	1	17
Crack-cocaine	Crack-cocaine-dependence	dlPFC (AR/CL)	2	36 + 14				dlPFC (AR/CL)	1	35
Methamphetamine	Methamphetamine use	right dlPFC (A)	1	30	right dlPFC (A)	1	30			
		dlPFC (AR/CL)	1	15						
Marijuana	Marijuana use	dlPFC (AR/CL)	1	25						
Heroin	Heroin-dependence	frontal-parietal-temporal (CR/CL)	1	20						
Cocaine	Cocaine-dependence							dlPFC (AR/CL)	1	8

* Electrode polarity over the targeted area is detailed between parentheses. The "/" character indicates a bilateral disposition over hemispheres.

A anode; B bilateral (meaning both anode right/cathode left and anode left/cathode right montages were tested); C cathode; dlPFC dorsolateral pre-frontal cortex; L left; OFC orbitofrontal cortex; R right.