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Stimulation of the Prefrontal Cortex Reduces Intentions to Commit Aggression: A Randomized, Double-Blind, Placebo-Controlled, Stratified, Parallel-Group Trial

Olivia Choy[1], Adrian Raine[2] and Roy H. Hamilton[3]

[1]*Department of Psychology, Nanyang Technological University, 14 Nanyang Drive, Singapore 637332*
[2]*Departments of Criminology, Psychiatry, and Psychology, University of Pennsylvania, Jerry Lee Center of Criminology, 3809 Walnut St, Philadelphia, PA 19104*
[3]*Department of Neurology, University of Pennsylvania, 3710 Hamilton Walk, Philadelphia, PA 19104*

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Corresponding Author: Olivia Choy, Nanyang Technological University, Department of Psychology, 14 Nanyang Drive, Singapore 637332. Email: oliviachoy@ntu.edu.sg

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Stimulation of the Prefrontal Cortex Reduces Intentions to Commit Aggression: A Randomized, Double-Blind, Placebo-Controlled, Stratified, Parallel-Group Trial.

Abbreviated Title: Prefrontal Stimulation Reduces Aggressive Intent

Olivia Choy [1] Adrian Raine,[2] and Roy H. Hamilton [3]

[1] Department of Psychology, Nanyang Technological University, 14 Nanyang Drive, Singapore 637332

[2] Departments of Criminology, Psychiatry, and Psychology, University of Pennsylvania, Jerry Lee Center of Criminology, 3809 Walnut St, Philadelphia, PA 19104

[3] Department of Neurology, University of Pennsylvania, 3710 Hamilton Walk, Philadelphia, PA 19104

Corresponding Author: Olivia Choy, Nanyang Technological University, Department of Psychology, 14 Nanyang Drive, Singapore 637332. Email: oliviachoy@ntu.edu.sg

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Abstract

Although prefrontal brain impairments are one of the best-replicated brain imaging findings in relation to aggression, little is known about the causal role of this brain region. This study tests whether stimulating the dorsolateral prefrontal cortex (DLPFC) using transcranial direct current stimulation (tDCS) reduces the likelihood of engaging in aggressive acts, and the mechanism underlying this relationship. In a double-blind, stratified, placebo-controlled, randomized trial, 81 human adults (36 males, 45 females) were randomly assigned to an active (N = 39) or placebo (N = 42) condition, and followed up one day after the experiment session. Intentions to commit aggressive acts and behavioral aggression were assessed using hypothetical vignettes and a behavioral task, respectively. The secondary outcome was the perception of the moral wrongfulness of the aggressive acts. Participants who received anodal stimulation reported being less likely to commit physical and sexual assault ($p < .01$), and judged aggressive acts as more morally wrongful ($p < .05$) compared to the sham controls. 31% of the total effect of tDCS on intentions to commit aggression was accounted for by perceptions of greater moral wrongfulness regarding the aggressive acts. Results provide experimental evidence that increasing activity in the prefrontal cortex can reduce intentions to commit aggression and enhance perceptions of moral judgment. Findings shed light on the biological underpinnings of aggression and theoretically have the potential to inform future interventions for aggression and violence.

Trial Registration ClinicalTrials.gov identifier: NCT02427672

Significance Statement

Aggressive behaviors pose significant public health risks. Understanding the etiology of aggression is paramount to violence reduction. Investigations of the neural basis of aggression have largely supported correlational, rather than causal interpretations, and the mediating processes underlying the prefrontal-aggression relationship remain to be well-elucidated. Through a double-blind, stratified, placebo-controlled, randomized trial, this study tested whether upregulation of the prefrontal cortex reduces the likelihood of engaging in aggression. Results provide experimental evidence that increasing prefrontal cortical activity can reduce intent to commit aggressive acts. They also shed light on moral judgment as one mechanism that may link prefrontal deficits to aggression and in theory, have the potential to inform future approaches towards reducing aggression.

Introduction

Prefrontal brain impairment is one of the best-replicated risk factors for aggressive behavior. Evidence from neurological research shows that patients with damage to the frontal cortex exhibit more aggressive behavior (Anderson et al., 1999). In addition to head injury and lesion studies, the imaging and neuropsychological literature has documented structural and functional prefrontal deficits in antisocial individuals (Brower and Price, 2001; Yang and Raine, 2009). Findings on the role of the frontal cortex in modulating aggression and violence also extend to sexual offending (Chen et al., 2016).

Within the prefrontal cortex, a meta-analysis of 43 imaging studies found that impairments of the dorsolateral prefrontal cortex (DLPFC) are implicated in antisocial behavior, with a stronger effect for the left (d = -.89) than right (d = -.56) DLPFC (Yang and Raine, 2009). This may be due to the DLPFC's broad connection to functions related to aggression, including moral judgment (Mendez, 2009), that can in turn influence the risk of engaging in aggression, a deduction consistent with the neural moral model of antisocial behavior (Raine and Yang, 2006). More recent findings bolster the meta-analytic evidence. The involvement of the DLPFC in aggressive and antisocial behavior has since been documented in other neuroimaging studies (e.g., Dalwani et al., 2011; Fairchild et al., 2013; Alegria et al., 2016). Furthermore, while it has been suggested that DLPFC lesions are associated with apathy and diminished motivation (Levy and Dubois, 2005), a meta-analysis of 126 neuropsychological studies measuring executive functions in antisocial populations documented an effect size of d = .44 for antisocial behavior and d = .41 for physical aggression, implicating dorsolateral prefrontal dysfunction in aggression (Ogilvie et al., 2011). It is important to recognize however that the DLPFC is not the only prefrontal area implicated in antisocial and aggressive behavior. Other sub-regions include the ventromedial prefrontal cortex (Hare et al., 2014) and anterior cingulate cortex (Kolling et al., 2016), areas which have widespread connections to the DLPFC. Taken together, studies suggest that there is multi-method evidence indicating the possible implication of the DLPFC on antisocial behavior, amongst other brain regions.

Despite these findings, little is known about the *causal* role of the prefrontal cortex on aggressive behavior. Conclusions from extant research on the neural foundations of aggression have largely been correlational. Three known studies have tested the effect of prefrontal cortex upregulation on aggression using the Taylor Aggression Paradigm and transcranial direct current stimulation (tDCS), a non-invasive technique that influences neural excitability by delivering a direct, continuous, low-intensity electrical current to cortical areas between anodal and cathodal electrodes (Brunoni et al., 2012). However, findings have been mixed. One study documented that upregulating the right DLPFC reduced proactive aggression in males (Dambacher et al., 2015a), while another revealed that increasing left DLPFC activity resulted in more aggressive behavior when participants were angry (Hortensius et al., 2011). In contrast, upregulation of the inferior frontal cortex did not have a significant effect on aggression (Dambacher et al., 2015b). Whether stimulation targeting the DLPFC can reduce intentions to engage in aggressive acts or behavioral aggression using other measures has not been examined and to our knowledge, no studies have experimentally investigated the intermediary mechanisms linking prefrontal deficits to aggression.

Given the association between prefrontal impairments and aggression, this study tests the hypothesis that upregulating the prefrontal cortex using tDCS will lower intent to commit an aggressive act. This study additionally extends the limited literature on tDCS and aggression by employing a larger sample. As similarities have been found between the neural mechanisms underlying moral cognition in normal individuals and brain mechanisms that are impaired in antisocial populations (Raine and Yang, 2006), we also assess whether prefrontal upregulation improves judgments of moral wrongfulness, which may in turn partly account for any effect of prefrontal enhancement on reducing intent to commit aggressive acts.

Methods

Trial Design

The study consisted of a double-blind, placebo-controlled, stratified, randomized trial comparing an anodal tDCS intervention with a sham control group. Baseline assessments and one session of tDCS or sham intervention were conducted during the experimental session, while outcome measures were assessed the following day. Tasks and questionnaires were administered in a fixed order. The study was approved by the Institutional Review Board of the University of Pennsylvania and the trial protocol was registered at ClinicalTrials.gov (NCT02427672).

Participants

Eighty-six healthy adults (≥ 18 years of age) were recruited in Philadelphia between April 2015 and April 2016. The experiment took place during the course of one visit to the study site. In addition to assessments conducted at baseline, participants were followed up one day after the experimental session using a web-based questionnaire. Exclusion criteria included contraindications to brain stimulation, including metallic implants near the electrode sites, unstable medical conditions, neurological, cardiovascular, or psychiatric illness, participation in another non-invasive brain stimulation study on the same day, history of adverse reactions to tDCS, and lack of email access. Written informed consent was obtained from all participants.

tDCS Intervention

tDCS was administered by trained study personnel using a battery-driven, constant-current stimulator (TCT Research). Two anodal electrodes were placed over the DLPFC bilaterally (F3 and F4) according to the International 10-20 EEG system. A constant current of 2mA (1mA to each DLPFC site) was applied for 20 minutes through saline-soaked sponge electrodes (5x5cm). A single extracephalic cathodal electrode (5x7cm) was placed at the posterior base of the neck in order to minimize unintentional effects of inhibitory stimulation on brain activity.

Following standard tDCS protocol, stimulation commenced after a 30-second ramp-up period. The current was ramped down over the last 2 seconds. The tasks performed during tDCS are understood to influence the behavioral after-effects of stimulation (Gill et al., 2015). Thus, during the stimulation session, all participants performed the Psychology Experiment Building Language (Mueller and Piper, 2014) version of two cognitive tasks that are known to engage the DLPFC, the Psychomotor Vigilance Task (Dinges and Powell, 1985; Cui et al., 2015), followed by the Iowa Gambling Task (Bechara et al., 1994; Ernst et al., 2002). Although participants in both intervention arms received the same electrode placement and ramp-up/down times, stimulation for the sham control group was discontinued after 30 seconds. This has proven to be effective for blinding as participants habituate to the sensation of stimulation within seconds of current initiation (Gandiga et al., 2006).

Intentions to commit aggression. Behavioral intentions to commit aggressive acts were assessed using two hypothetical vignettes, which have been studied in samples with similar characteristics to ours (Hannon et al., 2000; Mazerolle et al., 2003). Brief scenarios describing two types of aggression, physical assault and sexual assault, were presented to participants who responded to the anticipated likelihood that they would commit the aggressive act. Responses were measured on a scale ranging from zero (no chance at all) to ten (100 percent chance).

Perceptions of moral wrongfulness. To assess moral perceptions of the aggressive acts, participants were asked to rate how morally wrong it would be to act as the protagonist in the scenario on a scale from 0 (not at all) to 10 (very). Aggregate measures of aggressive intent and perception of moral wrongfulness were created by combining responses from the physical and sexual assault scenarios (Armstrong and Boutwell, 2012).

Aggression. The voodoo doll task is a reliable and validated behavioral analog measure of aggression (DeWall et al., 2013). In this task, participants were shown a computer-based image of a doll that represented a partner or a close friend. They were told that they were given the opportunity to release their negative energy to that individual by inserting as many pins (0-51) in the doll as they wished. Instructions did not use the word “voodoo”. Stabbing the doll with more pins indicated higher levels of aggression.

Randomization and Stratification

At the initial visit, participants were randomized into an active stimulation or sham/placebo condition using a computerized urn randomization procedure (Stout et al., 1994). The stratification factors were age (18 years/19 years/20 years and above), sex (male/female), and ethnicity (Caucasian/non-Caucasian). This stratification was used to balance groups on key demographic variables.

Blinding

Participants and experimenters were blind to the tDCS condition assignment. The trial adhered to established procedures to maintain separation between staff that conducted the stimulation and staff that engaged with the participant. In each experimental session, only one experimenter who set up the tDCS procedure had knowledge of the participant's allocation. To further ensure blinding, all participants were kept blind to the objective of the study and outcome measures were not taken in the presence of research staff as they could lead to biased results.

In the 3 cases where double blinding was compromised due to the inability of having more than one experimenter at a session, the cases were excluded from analyses. To assess adherence to blinding procedures, James' (James et al., 1996) and Bangs' (Bang et al., 2004) blinding indices were calculated using the participants' and blinded experimenters' guesses about group assignment at the end of the experimental session.

Statistical Analyses

One-way ANCOVA was used to test group differences in intentions to commit aggression and the behavioral measure of aggression. Baseline measures were examined as possible covariates: variety of crime throughout the lifetime, aggression, GPA, trait anxiety, social adversity, psychopathy, the lack of premeditation and sensation-seeking dimensions of impulsivity, and self-control.

In addition to a Self-Report Crime Questionnaire that asked participants to indicate the number of times they had committed 36 criminal and delinquent acts ranging from white-collar and blue-collar offenses (e.g. fraud and shoplifting) to non-criminal, deceptive behaviors (e.g., cheating on an exam), participants' baseline levels of aggression were assessed using the Reactive-Proactive Aggression Questionnaire (Raine et al., 2006). Trait anxiety was assessed using the 20-item Spielberger State-Trait Anxiety Inventory (Spielberger, 1983). A social adversity index was obtained based on responses to 14 items obtained from demographic questionnaires. Items included parent unemployment, mother's low education, father's low education, parental separation or divorce, placement in a foster home, hospital, or other institution during childhood, having 5 or more siblings, born to a teenage mother, a ratio of people per room (including bedrooms, living room, dining room, and kitchen) of 1.0 and above, brought up in public housing, parents' use of welfare or food stamps from the government, father or mother had been arrested, father or mother has had problems with alcohol or drugs, father or mother has had physical illness, such as heart or lung problems, father or mother has had mental illness, such as alcoholism, major depression, schizophrenia, or anxiety. To assess psychopathic traits, the short form of the Self-Report of Psychopathy-III (SRP-SF) questionnaire, comprising 29 items, was administered (Paulhus et al., 2009). Additionally, scores were obtained from the lack of premeditation and sensation-seeking subscales of the short-form version of the UPPS-P Impulsivity Scale (SUPPS-P) (Lynam, 2013), and self-control was assessed using the 13-item Brief Self-Control Scale (Tangney et al., 2004).

Following recommendations, stratification variables and baseline measures that were associated with the outcomes were adjusted for, while variables with baseline imbalances were not (Committee for Proprietary Medicinal Products, 2004; Kahan et al., 2014). Effect sizes were calculated using partial eta squared.

To provide information on a mechanism of action accounting for any effect of tDCS on aggressive intent, change in perceptions of moral wrongfulness was examined using ANCOVA. We tested whether enhanced moral judgment mediated group differences in intent to commit aggressive acts through a bootstrapping approach using the PROCESS macro on SPSS (Hayes, 2013). 10,000 bootstrapped samples were drawn from the original data. The indirect effect of tDCS on intent to commit aggression was calculated as the product of the regression coefficients for the relationship between tDCS and moral judgment and the association between moral judgment and aggressive intent. The percent mediated, P_M, is expressed as the ratio of the indirect to total effect of treatment group on intention to commit aggression (Ditlevsen et al., 2005; Hayes, 2013). Hypothesis tests were two-tailed. Blinding indices were obtained using STATA version 14.0 (Stata Corp, 2015). All other statistical analyses were conducted using SPSS version 24.0 (IBM Corp, 2016).

Results

Participant Flow and Recruitment

Data were analyzed on a total sample of 81 (see Figure 1 for details or reasons for loss). No participants were lost to follow-up. There was no evidence of selection bias as no significant differences were observed between participants who were included in the analyses and those who were not ($p > .05$; Table 1).

Demographics and Adherence to Protocol

Baseline distributions of the hypothesized covariates were generally well balanced between the treatment groups. With the exception of social adversity, demographic variables and baseline characteristics did not differ across groups (Table 2). As the James' blinding indices were greater than .5 and Bang's blinding indices did not approach 1 or -1, participants were considered to have been blinded successfully on average (Table 3) (James et al., 1996; Bang et al., 2004).

Aggression Outcomes

Prognostic covariates were determined based on bivariate associations between the hypothesized covariates and outcome measures (Table 4). A one-way ANCOVA controlling for self-report crime and baseline aggression levels revealed a main effect of treatment group on aggressive intent, with the active tDCS group reporting a significantly lower likelihood of engaging in aggression compared to the sham control group, F (1, 70) = 8.40, $p < .01$, $\eta_p^2 = .11$ (Figure 2A). There were no significant interaction effects between treatment group and sex, F (1, 70) = .57, $p = .45$, $\eta_p^2 = .01$, and between treatment group and ethnicity, F (1, 70) = .01, $p = .92$, $\eta_p^2 < .001$. Further analyses revealed that intent to commit both physical assault, F (1, 70) =

5.61, p = .02, η_p^2 = .07 and sexual assault, F (1, 70) = 5.64, p = .02, η_p^2 = .08 were lower in the active tDCS group (Figure 2A). However, there was no significant group difference in behavioral aggression assessed using the voodoo doll task, F (1, 71) = 1.31, p = .26, η_p^2 = .02 (Figure 2B). Additional sensitivity analysis conducted on log-transformed and square root-transformed data for the aggression measures yielded substantively similar findings (Figure 2-1).

Mechanisms Accounting for the Reduction in Intent to Commit Aggression

ANCOVA also revealed that compared to controls, the active tDCS group perceived aggressive acts as more morally wrong, F (1, 71) = 4.64, p = .04, η_p^2 = .06 (Figure 2C). In particular, the main effect of treatment group was significant for perceptions of moral wrongfulness regarding sexual assault, F (1, 71) = 6.81, p = .01, η_p^2 = .09, but not physical assault, F (1, 71) = .96, p = .33, η_p^2 = .01. Higher ratings of moral wrongfulness partly mediated the reduction in intention to commit aggressive acts (indirect effect: b = -.51, 95% CI -1.14 to -.10, $p < .05$). After controlling for perceptions of moral wrongfulness, treatment group was not a significant predictor of aggressive intent (Figure 3). 31% of the total effect of treatment group on overall aggressive intent was accounted for by moral perception.

Further analysis revealed that moral wrongfulness partly mediated the reduction in likelihood of committing sexual assault (indirect effect: b = -.34, 95% CI -1.11 to -.03, $p < .05$), but not physical assault (indirect effect: b = -.32, 95% CI -.89 to .10, $p > .05$). Perceptions of moral wrongfulness accounted for approximately half (P_M = .56) of the total effect of treatment group on intent to commit sexual assault. For completeness, sensitivity analyses that included the demographic variables and social adversity as covariates did not substantively change the mediation results (Figure 3-1).

Adverse Events

tDCS was associated with minimal side effects. No major adverse events were reported over the duration of the study. According to Fertonani et al.'s (2010) scale and consistent with other tDCS studies (Brunoni et al., 2012), reported side effects included itchiness (85.2%), lightheadedness (40.7%), pain (46.9%), burning (49.4%), warmth (51.2%), pinching (45.7%), iron taste (7.4%), and fatigue of light to moderate intensity (35.0%). No participants withdrew due to these minor events.

Discussion

This study tested a new approach to reducing aggressive and violent behavior. Individuals who underwent bilateral anodal stimulation of the DLPFC using tDCS reported a lower likelihood of committing an aggressive physical and sexual assault one day after stimulation compared to a sham control group. The treatment-aggressive intent relationship was partly accounted for by enhanced perception that the aggressive acts were more morally wrongful, resulting from prefrontal upregulation. Findings help to strengthen conclusions from neurological, neuroimaging, and neuropsychological research (Damasio et al., 1994; Damasio, 2000; Yang and Raine, 2009; Liljegren et al., 2015; Rogers and De Brito, 2016) by documenting experimentally the role of the prefrontal cortex on the likelihood of engaging in aggression and the perception of such acts as morally wrong.

Beyond examining experimentally the role of the prefrontal cortex on a behavioral symptom, the finding that moral judgment partly mediates the effect of tDCS on the likelihood of sexual assault contributes to our mechanistic understanding of the etiology of sexual violence. It also provides partial support for the neuro-moral theory of violent behavior that violence is due in part to impairments in brain regions subserving moral cognition and emotion (Raine and Yang, 2006). The null mediation effect observed for physical assault suggests that moral judgment plays a greater role on intentions to commit sexual assault, which is consistent with empirical evidence that sexual offenses such as rape are rated as more morally wrongful than physical violence (Akman et al., 1968; Hsu, 1973). This indicates that moral judgment is likely only one of several processes underlying the prefrontal-aggression relationship.

The difference in our results for behavioral intent and the behavioral measure of aggression warrant attention. Although participants in the tDCS group exhibited significantly lower levels of aggressive intent after the experimental session, they exhibited a non-significant increase (d = .26) in behavioral aggression. These null findings converge with the mixed findings on tDCS and behavioral aggression in the literature to date (e.g., Hortensius et al., 2011). Furthermore, a recent case study of two female patients receiving anodal tDCS over the left DLPFC and a cathode over the right DLPFC reported anger attacks post-stimulation, although notably, in contrast to the present study, these subjects were diagnosed with major depressive disorder (Hung and Huang, 2017).

Given empirical evidence that changes in intentions precede behavioral change (Webb and Sheeran, 2006), our results indicating lower intent to engage in aggressive acts following anodal prefrontal stimulation suggest that tDCS may be an *initial* step towards the reduction of aggression. This implication must however be tempered with the mixed findings in the extant literature. While the treatment and control groups did not differ on the behavioral measure of aggression, this finding is consistent with the concept that a single session of tDCS may have a limited effect on behavioral change. The longer-lasting therapeutic effects of tDCS are suggested to be associated with repeated, rather than single sessions of stimulation (Nitsche et al., 2008). Therefore, beyond intent to engage in aggression, future studies need to evaluate whether behavioral changes may be observed with more stimulation sessions.

Several caveats are in order. First, the trial findings are limited to an ostensibly healthy population. As the first study to test the effect of prefrontal cortical upregulation on aggressive intentions, the generalizability of the findings to other samples remains to be seen. A second limitation is that moral judgment and aggressive intent were measured concurrently. Thus, we were unable to confirm the temporal order of the mediator and outcome variable. However, empirical evidence that moral judgments shape behavior (Reynolds and Ceranic, 2007) provide support that the mediation model presented reflects the expected temporal effects. Third, this study measured aggressive inclinations one day after the intervention. Further research is needed to determine if tDCS can produce longer-term reductions in aggressive intent, as well as any reduction in aggressive behavior. Fourth, we were not able in our design to include stimulation of a "control" brain region to help document specificity of findings to the DLPFC**.** Although it has been documented that the right DLPFC is involved in moral judgment (Tassy et al., 2012), this study did not consider any laterality effects. Fifth, although the findings demonstrate that anodal tDCS resulting in a current flow through the DLPFC influences intentions to commit aggression, they do not negate the involvement of other prefrontal areas such as the ventromedial and anterior prefrontal cortex, or non-prefrontal areas including the temporal cortex. Future studies using complimentary non-invasive neurostimulation approaches such as transcranial magnetic stimulation and high definition-tDCS may elucidate the anatomical specificity of this effect and the complexity of the functional neuroanatomy of violent behavior.

There has been increasing discussion of biological interventions on antisocial and aggressive behavior in both children and adults (Gesch et al., 2002; Raine et al., 2015; Hübner and White, 2016). Our initial findings that are limited to intentions to commit aggression and moral judgment require extensive replication. Nevertheless, among other etiological mechanisms, the role of biological factors on the development of antisocial behavior, including aggression, has been increasingly acknowledged (Raine, 2002; Glenn and Raine, 2014; Latvala et al., 2015). It has been suggested that treatment programs will be improved by considering biological mechanisms that potentially regulate aggression (Beauchaine et al., 2008). Thus, it can be argued that further investigation of basic science trials on tDCS may potentially offer a promising new biological approach for reducing aggression, which is a major public health problem and a feature of a variety of mental disorders, including antisocial personality disorder, intermittent explosive disorder, conduct disorder, and borderline personality disorder (American Psychiatric Association, 2013).

Conclusion

Understanding the etiology of aggression and the development of new interventions are paramount to a public health approach to violence reduction (Butchart et al., 2004; Slutkin, 2017). This first known application of prefrontal tDCS to intentions to commit aggression takes a modest step towards advancing knowledge about the neural mechanisms that regulate aggression. Findings provide experimental evidence for the role of the prefrontal cortex on both physical and sexual assault, and suggest how the brain may, in theory, be amenable to change using a non-invasive tool with transient and relatively minor adverse effects (Poreisz et al., 2007; Fertonani et al., 2015). Nevertheless, a stronger evidence base which includes more consistent findings, documentation of long-term beneficial effects, and a comprehensive effort to rule out potentially aversive side effects is required before this technique can be considered in practice to reduce aggression perpetration.

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Table 1. Comparison of participants who were included and excluded in statistical analyses[a]

Characteristic	**Included (n = 81)**	**Excluded (n = 3)**	**Statistic**	***p* value**
Demographic variables				
Sex				
Female	45	1	Chi^2 = .58	.45
Male	36	2		
Age, y	20.21 (3.31)	20.00 (1.73)	t = .11	.91
Race				
Caucasian	36	1	Chi^2 = .15	.70
Non-Caucasian	45	2		
Baseline measures				
GPA[b]	3.59 (.77)	3.66 (.29)	t = -.17	.87
Social adversity	1.10 (1.48)	1.00 (1.00)	t = 2.32	
Variety of offending	16.85 (6.21)	15.00 (5.00)	t = .51	.61
Baseline aggression	9.37 (4.72)	10.33 (2.08)	t = -.35	.73
Psychopathy	23.17 (12.20)	23.00 (13.75)	t = .02	.98
Lack of premeditation	1.61 (.49)	1.92 (.14)	t = -1.08	.28
Sensation-seeking	2.89 (.64)	2.58 (.52)	t = .80	.42
Anxiety	38.60 (8.86)	45.67 (13.05)	t = -1.34	.19
Self-control	36.26 (6.95)	37.00 (1.73)	t = -.18	.86
Outcome variables				
Aggressive intent	2.26 (3.56)	1.33 (.58)	t = .45	.66
Aggression (voodoo doll task)	3.91 (10.29)	3.33 (5.77)	t = .10	.92
Moral wrongfulness	15.20 (3.48)	16.33 (3.51)	t = -.56	.58

[a]Data for continuous variables are presented as mean (SD), with comparisons conducted using independent samples *t*-tests or chi-square tests as appropriate.

[b]For 8 individuals missing data on GPA scores, mean imputation was conducted. Missing values were replaced with the mean of the observed data as suggested in Kahan et al. (2014).

Table 2. Baseline characteristics by treatment arm[a]

Characteristic	**tDCS group (n = 39)**	**Sham group (n = 42)**	**Statistic[b]**	***p* value**
Sex				
Female	24	21	Chi^2 = 1.09	.30
Male	15	21		
Age, y	20.26 (4.13)	20.17 (2.36)	t = -.12	.90
Race				
Caucasian	17	19	Chi^2 = .02	.88
Non-Caucasian	22	23		
GPA[c]	3.55 (.27)	3.47 (.33)	t = -1.18	.24
Social adversity	.72 (1.15)	1.45 (1.67)	t = 2.32	.02
Variety of offending	17.36 (6.25)	16.38 (6.22)	t = -.71	.48
Aggression	9.92 (4.97)	8.86 (4.48)	t = -1.02	.31
Psychopathy	23.33 (11.85)	23.02 (12.65)	t = -.11	.91
Lack of premeditation	1.59 (.49)	1.63 (.49)	t = .38	.71
Sensation-seeking	2.89 (.65)	2.88 (.65)	t = -.07	.94
Anxiety	38.79 (8.53)	38.43 (9.25)	t = -.19	.85
Self-control	37.05 (6.69)	35.52 (7.18)	t = -.99	.33

[a]Data for continuous variables are presented as mean (SD).
[b]Differences in baseline scores were compared using two-tailed independent *t*-tests and chi-square tests.
[c]For 8 individuals missing data on GPA scores, mean imputation was conducted. Missing values were replaced with the mean of the observed data as suggested in Kahan et al. (2014).

Table 3. Participant and experimenter conjectures about group assignment and blinding indices

	Participant's guess, n (%)						
Intervention	**tDCS**	**Sham**	**Do not know**	**Total**	James' BI	Bang's BI	95% CI[b]
tDCS	26 (32.1)	3 (3.7)	10 (12.3)	39 (48.1)		.59	.42, .76
Sham	18 (22.2)	9 (11.1)	15 (18.5)	42 (51.9)		-.21	-.41, -.02
Total	44 (54.3)	12 (14.8)	25 (30.9)	81 (100)	.57		.49, .65

	Experimenter's guess, n (%)						
Intervention	**tDCS**	**Sham**	**Do not know**	**Total**	James' BI	Bang's BI	95% CI
tDCS	12 (15.4)	0 (0)	25 (32.1)	37 (47.4)		.32	.20, .45
Sham	2 (2.6)	2 (2.6)	37 (47.4)	41 (52.6)		0	-.08, .08
Total	14 (17.9)	2 (2.6)	62 (79.5)	78 (100)[a]	.84		.76, .91

[a]Due to missing data, 3 cases were omitted from calculations of the blinding indices.
[b]CI = confidence interval

Table 4. Relationships between outcome variables (aggressive intent, moral wrongfulness, behavioral aggression) and baseline characteristics of the sample, assessed using *t*-tests for dichotomous demographic variables (upper section) and Pearson correlations for continuous baseline variables (lower section)

Characteristic	**Aggressive intent**	**Moral wrongfulness**	**Behavioral aggression**
Sex[a]	-2.10*	4.21***	.11
Race[b]	-.08	.06	-.52
Age	-.07	-.01	-.02
GPA	.13	.02	.15
Social adversity	-.08	.09	-.05
Variety of offending	.36**	-.21	.001
Aggression	.42***	-.07	.08
Psychopathy	.17	-.30**	.20
Lack of premeditation	-.07	.11	.28*
Sensation-seeking	.17	-.06	.19
Anxiety	-.02	-.07	.22
Self-control	.01	-.07	.22

[a]Sex was coded as 0 for female and 1 for male.
[b]Race was coded as 0 for Caucasian and 1 for non-Caucasian.
*p < .05; **p < .01; ***p < .001.

Figure 1. CONSORT flowchart of the screening and enrollment of study participants who were randomly assigned to anodal prefrontal stimulation or a sham control group

Figure 2. Group means for A) aggressive intent, B) behavioral aggression, and C) perceptions of moral wrongfulness at follow-up

Figure 3. Bootstrapped mediation model documenting that perceptions of greater moral wrongfulness mediated the effect of anodal tDCS on reducing intentions to commit aggression

Figure 2-1. Group means and SDs for log-transformed and square-root transformed antisocial behavior outcomes at follow-up

Figure 3-1. Total, direct, and indirect effects of tDCS on aggressive intent, controlling for demographic variables and social adversity

Figure 1. CONSORT flowchart of the screening and enrollment of study participants who were randomly assigned to anodal prefrontal stimulation or a sham control group

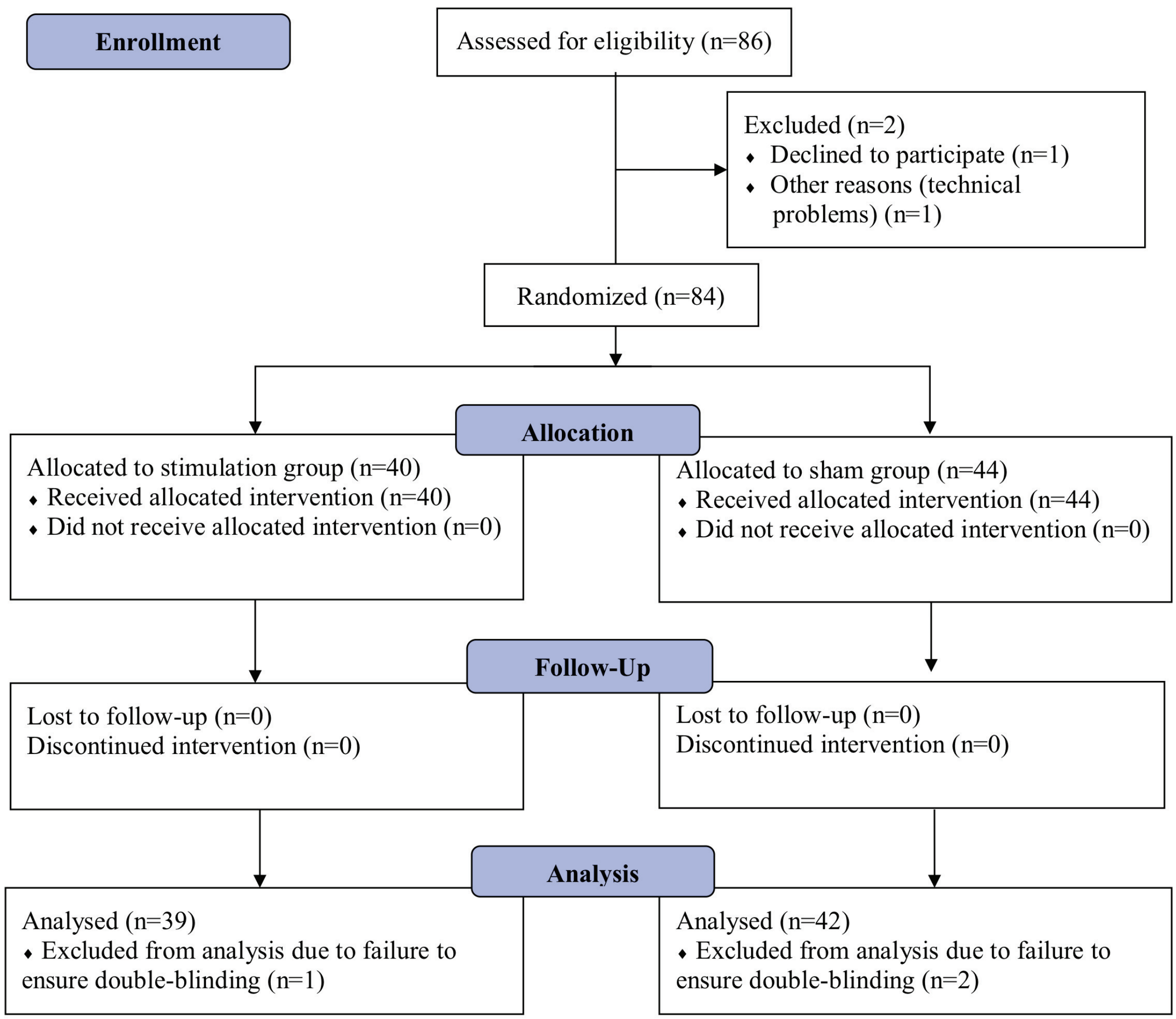
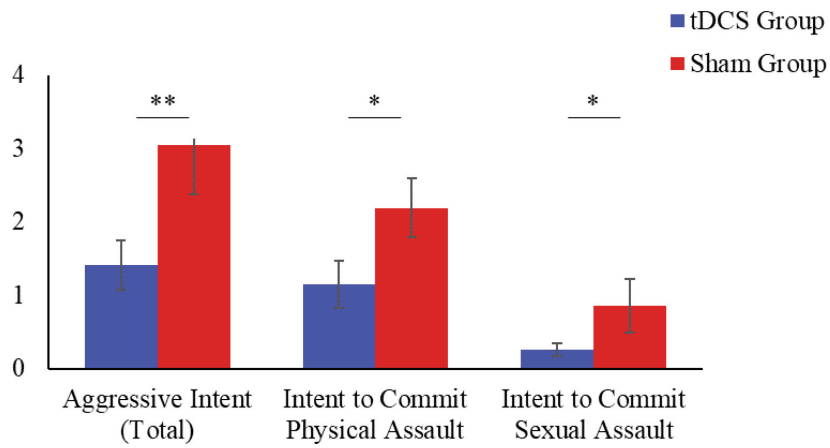


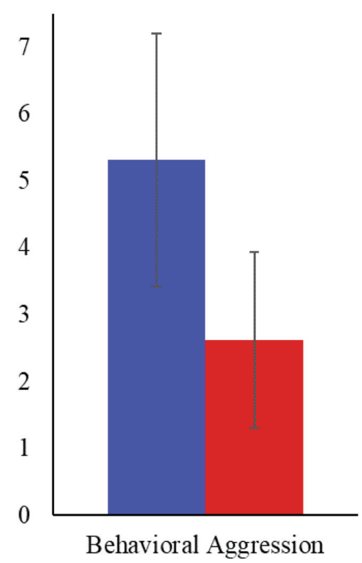
Figure 2. Group means for A) aggressive intent, B) behavioral aggression, and C) perceptions of moral wrongfulness at follow-up

A)



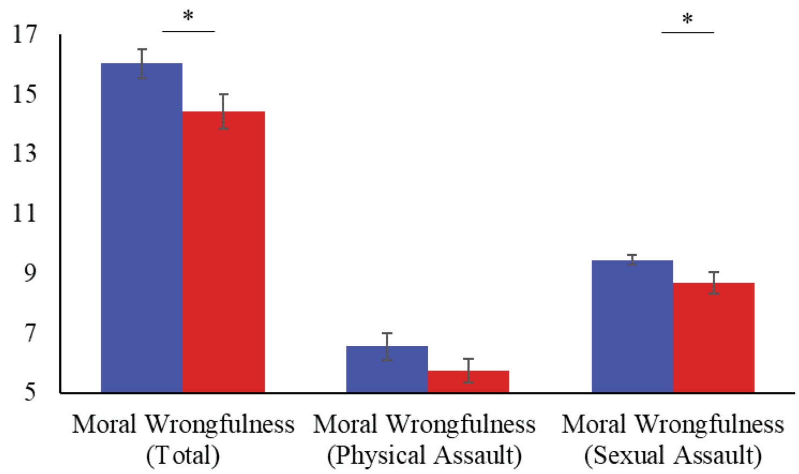
Note. Group effects were determined from ANCOVA, controlling for stratification variables (sex, age, ethnicity), self-report offending, and baseline aggression.
**p* < .05; ***p* < .01

B)



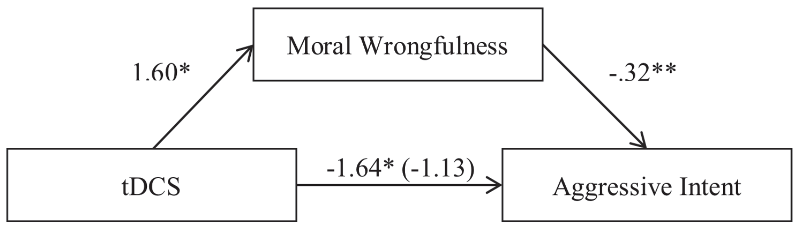
Note. Non-significant group effects were determined from ANCOVA, controlling for stratification variables (sex, age, ethnicity) and lack of premeditation scores.

C)



Note. Group effects were determined from ANCOVA, controlling for stratification variables (sex, age, ethnicity) and baseline psychopathy levels.
$*p < .05$; $**p < .01$

Figure 3. Bootstrapped mediation model documenting that perceptions of greater moral wrongfulness mediated the effect of anodal tDCS on reducing intentions to commit aggression



Note. The path coefficients are unstandardized. The value in parentheses indicates the direct effect of tDCS on intention to engage in aggression.
**p* < .05; ***p* < .01