THE IMPACT OF ANODAL tDCS ON THE ATTENTIONAL NETWORKS AS A FUNCTION OF TRAIT ANXIETY AND DEPRESSIVE SYMPTOMS: A PREREGISTERED DOUBLE-BLIND SHAM-CONTROLLED EXPERIMENT

Charlotte Coussement, Monica Riesco de Vega, and Alexandre Heeren

Abstract

Attention is a multifaceted construct, including three distinct attentional networks: the alerting, orienting, and executive conflict networks. Recently, researchers have started to envision strategies to enhance the attentional networks, and transcranial Direct Current Stimulation (tDCS) has emerged as a promising tool to do so, especially regarding the executive conflict network. On the other hand, other research lines have suggested that anodal tDCS might yield more substantial impacts among depressive and anxious participants. In this preregistered study, we thus examined two questions. First, we wanted to replicate previous observations and tested whether anodal tDCS does improve the executive conflict network's efficiency. Second, we set out to clarify the impact of anxiety and depressive symptoms on this effect. To do so, we adopted a double-blind within-subject protocol in an unselected sample (n = 50) and delivered a single session of anodal— applied over the dorsolateral part of the left prefrontal cortex—versus sham tDCS during the completion of a task assessing the attentional networks. We assessed anxiety and depressive symptoms at baseline. Although there were no significant direct effects of tDCS on the attentional networks, we found that the higher the levels of depression and trait anxiety, the larger the executive conflict network's enhancement during tDCS. By highlighting the importance of trait anxiety and depression when considering the impact of tDCS on the attentional networks, this study fulfills a valuable niche in clinical neuroscience, wherein preclinical data provide critical clues for larger, more definitive future translational efforts.

Key words: neuromodulation, transcranial direct current stimulation, attentional networks, executive control, trait anxiety, depression, preclinical research

Charlotte Coussement[1,2], Monica Riesco de Vega[3], and Alexandre Heeren[1,4]

[1] Psychological Sciences Research Institute, Université catholique de Louvain, Louvain-la-Neuve, Belgium
[2] Department of Clinical Research and Scientific Publications, Le Beau Vallon – Psychiatric Hospital, Namur, Belgium
[3] Department of Sport Science, Polytechnic University of Madrid, Madrid, Spain
[4] Institute of Neuroscience, Université catholique de Louvain, Brussels, Belgium

Charlotte Coussement https://orcid.org/0000-0002-4549-9904
Monica Riesco de Vega https://orcid.org/0000-0001-7222-1660
Alexandre Heeren https://orcid.org/0000-0003-0553-6149

Citation: Coussement, C., de Vega, M.R., Heeren, A. (2020). The impact of anodal tDCS on the attentional networks as a function of trait anxiety and depressive symptoms: A preregistered double-blind sham-controlled experiment. *Clinical Neuropsychiatry, 17*(4), 225-235.

doi.org/10.36131/cnfioritieditore20200404

Funding: Charlotte Coussement was supported by a research fellowship from the "Beau Vallon Psychiatric Hospital" (Grant "G01180016"), Monica Riesco de Vega was supported by the Erasmus+ Program scheme, and Alexandre Heeren was supported by the F.R.S.-FNRS Belgian Science Foundation (Grant "1.C.059.18F").

Competing interests: None.

Corresponding author
Alexandre Heeren, Psychological Sciences Research Institute, Université catholique de Louvain, 10 Place du Cardinal Mercier, 1348 Louvain-la-Neuve, Belgium.
E-mail: alexandre.heeren@uclouvain.be

A vital concern for any living creature is the need to pay attention to crucial information amid all the irrelevant distractors that orbit around us. Over the last decades, several prominent attention models have been proposed to account for attention's multifaceted nature (Corbetta & Shulman, 2002; Fan et al., 2005; Posner & Rothbart, 2007). Among them, the model pioneered by Posner and Petersen (1990) has quickly become a hot topic in contemporary research on attention.

According to this perspective (Petersen & Posner, 2012; Posner & Petersen, 1990), attention can be conceptualized as a multifaceted construct including three functionally and neuroanatomically distinct but overlapping attentional subsystems (e.g., Fan et al., 2005; Petersen and Posner, 2012; Posner and Rothbart, 2007). These are the alerting network (i.e., maintenance of alertness), the orienting network (i.e., selective engagement and disengagement with certain stimuli rather than others), and the executive conflict network of attention (i.e., top-down control of attention exemplified by the maintenance of attention on certain stimuli and resisting distraction by other stimuli). These networks play a critical role in regulating behavior, both in the control of positive and negative affect and of the sensory input, and give rise to consciousness of content and voluntary behaviors (e.g., Moriya & Tanno, 2009; Tortella-Feliu et al., 2014).

Given its prominence in contemporary literature, many studies have relied on this framework to delineate specific attentional impairments in clinical populations

Submitted July 2020, accepted July 2020

with psychiatric (e.g., Heeren, Maurage et al., 2015; Lannoy et al., 2017; Maurage et al., 2014; Wang et al., 2020; for discussion, see Heeren, Billieux et al., 2015; Lannoy et al., 2019) and neurological disorders (e.g., Heeren et al., 2014; Maurage et al., 2017; Togo et al., 2015). Not surprisingly, research has also started to envision strategies to enhance, and potentially restore, the three distinct attentional networks. In this way, researchers examined the impact of clinical interventions on the attentional subsystems (e.g., Heeren, Mogoaşe et al., 2015; Jha et al., 2007; Kwak et al., 2020; for a discussion, see Posner et al., 2019). Among these options, transcranial Direct Current Stimulation (tDCS) has been identified as a promising tool to modify the attentional networks (e.g., Lo et al., 2019; Roy et al., 2015), and especially the executive conflict network of attention (e.g., Miler et al., 2017; Silva et al., 2017).

tDCS is a noninvasive brain neuromodulation technique that can modulate cognitive and motor domains through the modulation of brain cortical excitability (e.g., Fregni & Pascual-Leone, 2007; Nitsche & Paulus, 2001). It consists of the application of a weak, direct electric current that flows from the anode to the cathode. These two electrodes are positioned over one's scalp to reach the neuronal tissue and induce polarization-shifts on the resting membrane potential without triggering action potentials per se (e.g., Brunoni et al., 2012; Nitsche et al., 2008). Anodal stimulation increases cortical excitability, whereas cathodal tDCS decreases it (Nitsche & Paulus, 2000).

Because of its noninvasive nature, and relatively low cost compared to other neuromodulation techniques (e.g., transcranial magnetic stimulation), tDCS has quickly emerged as a promising therapeutic tool. Indeed, many several systematic reviews and meta-analyses of randomized controlled trials indicated the safety and beneficial impact of anodal tDCS on a wide range of cognitive processes (for meta-analyses, see Brunoni & Vanderhasselt, 2014; Hill et al., 2016) as well as in the alleviation of symptoms of various psychiatric disorders (for comprehensive reviews, see Kekic et al., 2016; Mondino et al., 2014; Tortella et al., 2015).

Regarding the impact of tDCS on the attentional networks, most of the previous research suggests that one may modulate the attentional networks, and especially the executive conflict network of attention, via the application of anodal tDCS over the dorsolateral part of the left prefrontal cortex (hereafter, left dlPFC; e.g., Miler et al., 2017; Silva et al., 2017). However, although departures from this protocol—that is, changes in the targeted brain regions— have been associated to changes in the alerting and orienting networks of attention (e.g., Coffman et al., 2012; Trumbo et al., 2014), several researchers failed to replicate the effect of dlPFC-based tDCS anodal on the executive conflict network of attention (e.g., Chalah et al., 2017; Coussement et al., 2019; Roy et al., 2015). On the other hand, most of these studies had relatively small sample sizes (e.g., n = 10, Chalah et al., 2017; n = 20, Coussement et al., 2019). As such, uncertainty thus remains regarding the impact of tDCS on the executive conflict network of attention.

Moreover, prior research (including meta-analyses) have shown that anodal tDCS over left dlPFC may yield larger impacts (i.e., effect sizes) on cognitive tasks' performance among clinical populations, and especially among samples with depressive symptoms, social anxiety, or with elevated trait anxiety, than healthy ones (e.g., Brunoni & Vanderhasselt, 2014; Dedoncker et al., 2016; Hill et al., 2016). Ferruci et al. (2009) even suggested that the more severe the symptomatology, the more effective the technique. Regarding the impact of tDCS on the executive conflict network of attention, one may thus wonder about the influence of depression and anxiety symptoms, especially given the study-to-study variations in terms of samples in prior research. And, to date, this question has never been examined.

Based on the research mentioned above, the main goals of this project are twofold. First, we wanted to replicate whether anodal tDCS over the left dlPFC yields improvement in the efficiency of the executive conflict network of attention (hereafter, Hypothesis 1). Second, we wanted to examine whether this effect is influenced by participants' depression and anxiety levels. Based on the existing literature regarding tDCS (e.g., Dedoncker et al., 2016; Ferruci et al., 2009) and the attentional networks in anxiety and depression (e.g., Bellaera, & von Mühlenen, 2017; Heeren et al., 2019), we predicted that the higher the levels of trait anxiety, social anxiety, and depressive symptoms, the larger the impact of anodal tDCS on executive conflict (hereafter, Hypothesis 2).

Method

Preregistration and Open Science Practices

Following the recommendations of Medina and Cason (2017) for tDCS research, the design, analysis plans, and hypotheses for this study were preregistered at https://osf.io/x4quy. De-identified data are publicly available via the Open Science Framework and can be accessed at https://osf.io/5d9hm/.

A priori power analysis

As stated in our preregistration (https://osf.io/x4quy), we conducted an *a priori* power analysis to determine the appropriate total sample size for testing hypotheses with the primary outcome variables. Based upon previous studies examining the impact of anodal tDCS on the attentional networks among healthy volunteers (i.e., Miler et al., 2017), our goal was to obtain .95 power to detect a medium effect size of .76 (as in Miler et al., 2017) at the standard .05 alpha error probability. We obtained a value of n = 28.52 and decided to target a total sample of n= 50 in case we would encounter dropouts among our participants.

Participants

We recruited 50 right-handed Belgian French-speaking volunteers (32 women, 64 %) from the UCLouvain's community via media and listserv advertisements. In line with previous research on the impact of tDCS on attentional networks (e.g., Coussement et al., 2019; Miler et al., 2017), we relied on an unselected community sample to avoid potential problems of range restriction and maximize generalizability.

Participants with metal or electronic implants, epilepsy, pregnancy, cardiovascular disease, lifetime history of psychiatric/alcohol/drug dependence, current pharmacological or psychological treatments, corrective eyewear for altered vision, or insufficient knowledge of French language were excluded before participating to the experiment. Participants were between the ages of 18 and 37 (M = 23.26, SD = 3.35). Their years of education completed since primary school ranged from 11 to 21 (M = 15.56, SD = 2.52). Participants' characteristics appear in **table 1**.

Table 1. *Demographic and clinical characteristics of the participants*

	Mean (*SD*)	Cronbach's alpha
Demographic measures		
Age	23.26 (3.35)	
Educational level (in years)	15.56 (2.52)	
Gender ratio (F/M)	32/18	
Psychopathology		
BDI-II	7.54 (7.83)	.91
STAI-T	40.44 (10.21)	.89
LSAS	40.22 (22.71)	.95

Note. Education level was assessed according to the numbers of years of education completed after starting primary school. Cronbach's alphas were computed over the data of the current sample.
BDI-II, Beck Depression Inventory; STAI-T, Spielberger State-Trait Anxiety Inventory-Trait version; LSAS, Liebowitz Social Anxiety Scale.

Measures and Materials

Questionnaires assessing anxiety and depression.

To assess depression, social anxiety, and trait anxiety, we administrated the Beck Depression Inventory (BDI-II, Beck et al., 1998), the self-report version of the Liebowitz Social Anxiety Scale (LSAS; Liebowitz, 1987), and the Trait Anxiety Inventory (STAI-T; Spielberger et al., 1983), respectively. The questionnaires were administered before starting the experiment. The BDI-II is a 21-item self-reported questionnaire measure of symptoms of depression. The LSAS is a 24-item scale that measures fear and avoidance experienced in a range of social and performance situations over the last two weeks before completion. The STAI-T is a 20-item self-report questionnaire assessing anxiety proneness. For each measure, we used the validated French version of the scales (BDI; Beck et al., 1998; STAI-T; Bruchon-Schweitzer & Paulhan, 1993; LSAS; Heeren et al., 2012). For each scale, the internal reliability was high in the present sample. Cronbach's alphas are presented in **table 1**. For each scale, we computed total scale score, with higher score values denoting greater symptomatology.

Attention Networks Task (ANT)

We assessed the efficiency of the three independent attentional networks (i.e., alerting, orienting, and executive control) via the ANT (Fan et al., 2002). Participants had to determine as quickly and accurately as possible the direction of a central arrow (the target) located in the middle of a horizontal line projected either at the top or at the bottom of the screen. They responded by pressing the corresponding button (left or right) on the keyboard. Each target was preceded by either no cue, a center cue (an asterisk replacing the fixation cross), a double cue (two asterisks, one appearing above and one below the fixation cross), or a spatial cue (an asterisk appearing above or below the fixation cross and indicating the location of the upcoming target). Moreover, flankers appeared horizontally on each side of the target. There were three possible flanker types: either two arrows pointing in the same direction as the target (congruent condition), two arrows pointing in the opposite direction of the target (incongruent condition), or two dashes (neutral condition). Each trial had the following structure: (1) a central fixation cross (random duration between 400 and 1600 ms); (2) a cue (100 ms); (3) a central fixation cross (400 ms); (4) a target and its flankers, appearing above or below the fixation cross (the target remained on the screen until the participant responded or for 1700 ms if no response occurred); (5) a central fixation cross [lasting for 3500 ms minus the sum of the first fixation period's duration and the reaction time (RT)]. RT (in ms) and accuracy (percentage of correct responses) were recorded for each trial. **Figure 1** depicts a schematic representation of the ANT.

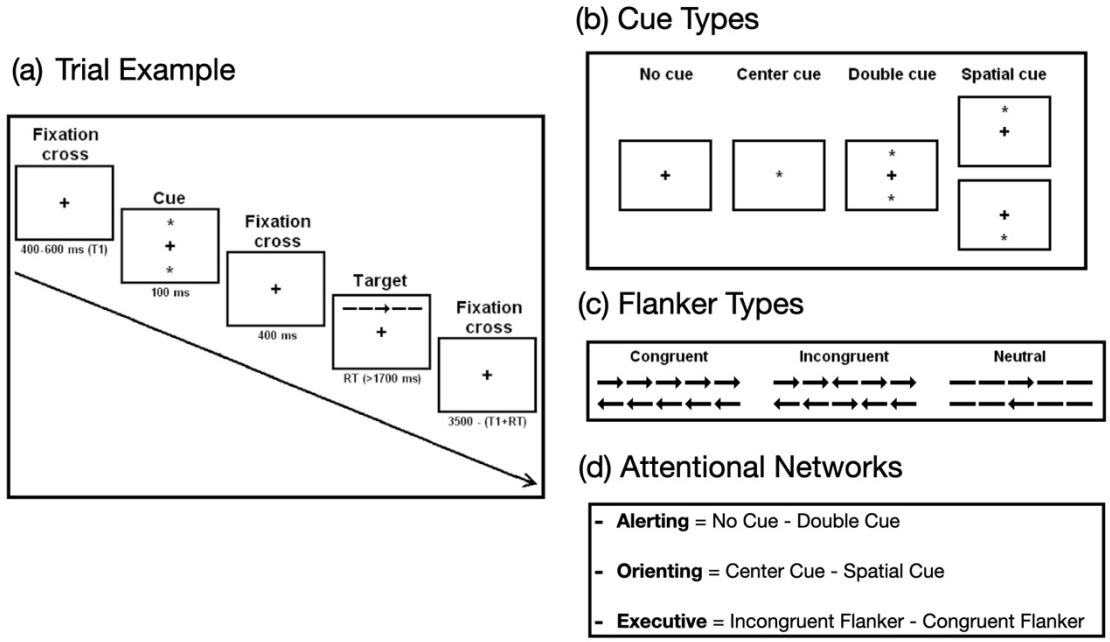
The ANT task comprised 288 trials, divided into three blocks of 96 trials each (with a short break between blocks). There were 48 possible trials, based on the combination of four cues (no cue, center cue, double cue, spatial cue; see **figure 1b**), three flankers (congruent, incongruent, neutral; see **figure 1c**), two directions of the target arrow (left, right; see **figure 1**) and two localizations (upper or lower part of the screen; see **figure 1**). Trials were presented in random order, and each possible trial was presented twice within a block. The task was programmed and presented via E-Prime 2.0 Professional® (Psychology Software Tools, Pittsburgh, PA, USA).

Following previous studies (e.g., Heeren et al., 2014; Lannoy et al., 2017; Maurage et al., 2014, 2017), we first excluded data from trials with incorrect responses and RTs lower than 200 ms or greater than 2000 ms for each participant at each session. Following Fan et al. (2002), we then computed the alerting effect by subtracting the mean (i.e., RT or accuracy score) for double cue trials from the mean for no cue trials (No cue – Double cue); the orienting effect by subtracting the mean for spatial cue trials from the mean result for center cue trials (Center cue – Spatial cue); and the executive conflict effect by subtracting the mean for congruent trials (summed across cue types) from the mean for incongruent trials (Incongruent – Congruent). For both alerting and orienting effects, greater subtraction scores for RT indicate greater efficiency. In contrast, greater subtraction scores for RT on executive conflict indicate increased difficulty with executive control of attention (Fan et al., 2005). **Figure 1d** summarizes the computation of the scores.

Transcranial direct current stimulation

Direct electrical current was delivered via a NeuroConn DC-Stimulator Plus device, with an integrated "double-blind study mode" (Neuroconn, GmbH, Ilmenau, Germany) and applied via a saline-soaked (i.e., with a 0.9% concentration of NaCl sodium chloride) pair of surface sponge rubber electrodes (35 cm2). We used a sham-controlled within-subject design, so that all participants serve as their own control—a

Figure 1. *Description of the Attention Network Task*



Note. (a) a trial example; (b) the four possible cues; (c) the six possible targets; (d) the scores computation. Adapted from Fan et al. (2002)

design that substantially increases statistical power. In line with previous studies (e.g., Coussement et al., 2019), we stimulated the left dlPFC. To do so, we vertically positioned the anode electrode over F3 of the 10–20 international system for electroencephalogram electrode placement. The reference electrode (i.e., the cathode) was placed vertically over the ipsilateral arm (Cogiamanian et al., 2007; Priori et al., 2008). During the first 30 seconds of stimulation, the current was ramped up to 2 mA and then delivered consistently for 25 minutes. At the end of the stimulation, the current was ramped down to 0 mA over 30 seconds. For the sham stimulation, the electrodes' position was identical to the anodal stimulation; however, the current was ramped down to 0 mA after 30 seconds. This procedure is commonly used in tDCS research and is known to be an optimal way to provide the initial sensation of stimulation without the subsequent effects on cortical excitability (e.g., Nitsche et al., 2008; Ohn et al., 2008).

Predefined codes assigned to either sham or real stimulation were used to start the stimulator and thus allowed for a double-blind study design. Anodal stimulation, or sham stimulation, respectively, started five minutes before the beginning of the ANT and was delivered for a further 20-min period (see the Procedure below). Hence, the ANT was executed simultaneously to the stimulation. To be consistent with previous tDCS studies in the field (e.g., Fregni et al., 2005; Heeren et al., 2017), the second stimulation was carried out after an exact 48h-interval to avoid carry-over effect.

Procedure

Each participant was tested individually in a dimly lit and quiet room. Participants first completed questionnaires. Then, the two 25-min stimulation-sessions were conducted. At the beginning of each stimulation, the electrodes were soaked in saline solution and placed on the participant's scalp using the electrode montage depicted above. The order of two tDCS-stimulation conditions was counterbalanced across participants (i.e., 25 participants first received the anodal stimulation; 25 participants first receiving the sham stimulation), and the second stimulation was carried out after an exact 48h-interval. For each session, participants started with the ANT after a 5-min stimulation (anodal or sham tDCS). This 5-min period was used to ensure that participants were accustomed to both the tDCS sensations (e.g., tingling, itching, or warming sensations) and the ANT's instructions (via a practice session) before starting the actual ANT. This practice session consisted of 24 randomly selected trials. Note that the experimenter recalled the instructions and answered the remaining questions before starting the actual ANT measurement. Then, at the exact end of this 5-min period, the actual ANT measurement started. The ANT lasted approximately 20 minutes—i.e., until the end of the tDCS stimulation. Participants were asked to perform the ANT's task as quickly and accurately as possible. There were no dropouts between the two sessions. The results of the 50 participants were thus included in the analyses.

The study was approved by the Institutional Review Board at the first author's university and conducted according to the Declaration of Helsinki. Each participant provided informed consent before completing the study, was fully debriefed upon completing, and was compensated 20€.

Preregistered data analysis plan

First, we computed a 2 (Stimulation) X 3 (attention networks) repeated-measures ANOVAs for RT with Stimulation (anodal tDCS, Sham) and Attention Network (Alerting, Orienting, Executive Conflict) with repeated measurement on the two factors and the network efficiency scores as dependent variables to investigate the impact of tDCS on the efficiency of three ANT networks. We predicted that anodal tDCS yields larger impact on the executive networks than the altering and orienting networks (i.e., Hypothesis 1)

Second, we examined whether anxiety and depression indices were associated with the tDCS-induced improvement in the efficiency of the attentional networks. For both alerting and orienting networks,

tDCS-induced improvement scores were computed as the difference between anodal tDCS score and sham tDCS score. In contrast, because greater subtraction scores for RT on executive conflict indicate increased difficulty with executive control of attention (Fan et al., 2005), tDCS-induced improvement score was computed as the difference between sham tDCS score and anodal tDCS score, so that higher values reflect greater improvement. As stated in our preregistration, we predicted that the potential effect of anodal tDCS on the efficiency of the executive network of attention would vary as a function of the level of mood and anxiety symptomatology. Especially, we predicted that the higher the level of psychopathology, the larger the impact of anodal tDCS on the executive network of attention (Hypothesis 2). To quantify the strength of the associations between each network efficiency and the indices of depression and anxiety, we computed the Pearson product-moment correlations between these variables and, to correct for chance capitalization, we used the Benjamini-Hochberg procedure to hold the false discovery rate at 5% for the 9 correlations of interest (Benjamini & Hochberg, 1995).

All statistical analyses were performed using SPSS software package (version 20.0). The significance level was set at an alpha level of .05 (bilateral). Effect sizes are reported in the form of partial eta-squared (η2p) for ANOVA and Cohen's *d* using the formula for paired *t*-test comparison (i.e., mean pairs difference divided by the pooled *SD*).

Results

Impact of tDCS on the Efficiency of the Attentional Networks (Hypothesis 1)

The Stimulation x Network interaction was not significant, $F(2,38) = 0.07$, $p = .93$, $\eta 2p < .01$, implying that the stimulation did not modulate the attentional networks (as predicted by our Hypothesis 1). Likewise, the main effect of Stimulation, $F(1,19) = .37$, $p = .55$, $\eta 2p = .01$, was not significant. The main effect of Network, $F(2,19) = 130.04$, $p < .0001$, $\eta 2p = .87$, was, however, significant and implying that the three networks did differ. Results appear in **figure 2**.

For each attentional network, we also computed paired comparison *t*-tests between anodal and sham tDCS. As shown in **figure 2**, none of the paired comparison *t*-tests was significant [alerting network: $t(49) = .75$, $p = .46$, $d = .11$; orienting network: $t(49) = 1.51$, $p = .14$, $d = .21$; executive conflict network: $t(49) = .61$, $p = .55$, $d = .09$]

Relations with anxiety and mood symptomatology indices (Hypothesis 2)

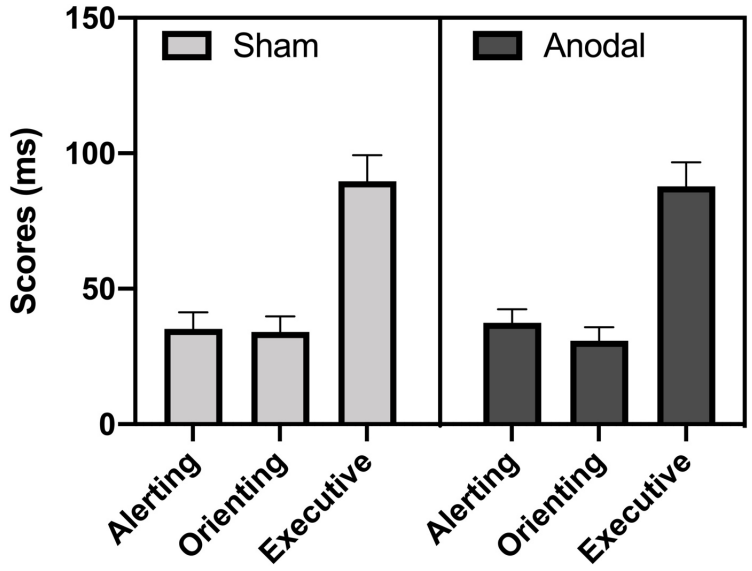
Table 2 depicts the correlations between the tDCS-induced improvements (i.e., score gains) in the efficiency of the attentional networks and the indices of anxiety and depression psychopathology. In line with our preregistered prediction (i.e., Hypothesis 2),

Table 2. *Correlations coefficient between networks improvement following anodal tDCS and indices of anxiety and mood psychopathology*

	Alerting gains	Orienting gains	Executive gains
LSAS	-.13	.15	-.08
BDI	-.02	.14	**.38****
STAI-T	.12	.10	**.34****

**, $p < .01$ after correction for multiple comparisons using the Benjamini–Hochberg false discovery rate procedure

Figure 2. *Differential latencies (in milliseconds) for the three attentional networks as a function of the stimulation*



Note. Error bars show standard errors

tDCS-induced improvement in the efficiency of the executive network was significantly associated with trait anxiety and depression, but not with social anxiety. For both trait anxiety and depression, the higher the levels of psychopathology, the larger the tDCS-induced improvement in the efficiency of the executive network during anodal tDCS—that is, as predicted by our hypothesis 2. There were no other significant correlations.

Discussion

In this preregistered study, we set out to examine two questions. First, we wanted to determine to what extent one can replicate the observation that anodal tDCS over the left dlPFC improved the efficiency of the executive conflict network of attention. In this way, we hypothesized that anodal tDCS over the left dlPFC should increase the efficiency of the executive conflict network of attention, as compared to the sham condition (Hypothesis 1). Second, in keeping with prior meta-analyses (e.g., Dedoncker et al., 2016) reporting that anodal tDCS over the left dlPFC yielded larger impacts (i.e., effect sizes) on cognitive tasks' performance among depressive and anxious samples (Brunoni & Vanderhasselt, 2014; Dedoncker et al., 2016; Hill et al., 2016), we set out to clarify the influence of anxiety and depressive symptoms in the malleability of the executive conflict network of attention during anodal tDCS. In this way, we predicted that higher levels of depression and anxiety should lead to a larger improvement in the efficiency of the executive conflict network of attention during anodal tDCS (Hypothesis 2).

Our results lent some support to the second hypothesis, but no evidence was found to support the first hypothesis. In contrast with our first hypothesis (Hypothesis 1), there was no difference between anodal and sham tDCS for any of the three attentional networks, thus suggesting that anodal stimulation did not modulate, in average, the attentional networks in the present study. On the other hand, the tDCS-induced improvement in the executive network's efficiency was significantly associated with trait anxiety and depression severity, but not with social anxiety. This latter finding partially aligns with our second prediction (Hypothesis 2). There are several explanations for this unexpected pattern of results.

First, one cannot exclude that dlPFC-based anodal tDCS may only yield beneficial effects among participants who require a "neural" boost during the ANT (e.g., Horvath et al., 2015; Medina & Cason, 2017). We believe the following analogy to be especially illustrative of our concern. If one were to give a person a crutch to help them walking, one might expect that this would only be helpful if the person does present locomotor impairments justifying such an aid. In contrast, if one does not require such assistance, a crutch would not improve one's locomotion—it may eventually lead to detrimental effects. Regarding our study, the transient tDCS neural boost within the left dlPFC may only benefit those who do require such a neural boost. Prior research indeed reported that individuals with depression or elevated trait anxiety exhibited impairments in the executive conflict network of attention (e.g., DeJong et al., 2019; Hammar et al., 2019; Wang et al., 2020) as well as reduced activation of the dlPFC when performing tasks involving such a network (e.g., Bishop et al., 2009; De Raedt & Koster, 2010; Hu et al., 2017; Wang et al., 2008). Thus, it is not surprising that we should consider the severity of depressive symptoms and trait anxiety for our effects to appear. Moreover, given that prior studies indicated that social anxiety was associated with impairments in the orienting network of attention but not with the executive conflict network (e.g., Heeren, Maurage et al., 2015; Heeren & McNally, 2016; Moriya & Tanno, 2009; Wang et al., 2020), the absence of an association between the former and the improvement of the latter during anodal tDCS should not come as a surprise. In contrast, it echoes research suggesting that interventions aiming at targeting a specific cognitive process should only be delivered in case of exhibited alterations of the incriminated process (e.g., Grafton et al., 2017; Kuckertz et al., 2014; Mogoaşe et al., 2014; but see Heeren, Philippot et al., 2015). Likewise, although PFC areas, and especially the left dlPFC, are assumedly considered as key regions in depression and trait anxiety research (e.g., Bishop, 2009; De Raedt & Koster, 2010; Hare & Duman, 2020; Heeren et al., 2013), the implications of PFC regions in social anxiety are less apparent (e.g., Bas-Hoogendam & Westenberg, 2020; Brühl et al., 2014; Heeren, Dricot et al., 2017). Unfortunately, our study was not designed to examine these questions. A critical step in future iterations would thus be to recruit only participants who actually exhibit impairments in the executive conflict network of attention or, ideally, show a reduced dlPFC activation during the ANT's completion.

Second, although our decision to place the anode over the left dlPFC was built upon previous studies showing the beneficial effect of anodal tDCS on the executive conflict network of attention (i.e., Miler et al., 2017; Silva et al., 2017), we slightly departed from these studies in terms of reference electrode's placement (i.e., the anode in case of cathodal stimulation and the cathode in case of anodal stimulation). Indeed, both Miler et al. (2017) and Silva et al. (2017) positioned the anode over the left dlPFC and the reference electrode over the contralateral supraorbital area. Ours was placed over the ipsilateral arm. This decision was based upon previous works indicating that the position of the reference electrode may influence the overall current flow pattern through the brain (Moliadze et al., 2010), and thus bias the effect as they may therefore no longer be specific to the influence of the neural boost of the brain region under the anode but also reflect the decreased cortical excitability of the brain region under the cathode (e.g., Bikson et al., 2010; DaSilva et al., 2011). However, although our montage aimed at safeguarding us against such an artifact, one cannot exclude that its wider inter-electrode distance impacted the intensity of the current stimulation under the anodal electrode (e.g., Moliadze et al., 2010). Of course, one may question the relevance of this explanation if it explains only our lack of support regarding the first hypothesis but cannot tell us anything about our partial confirmation of the second hypothesis. However, uncertainties remain regarding whether (sub)clinical populations may benefit from a distinct placement of the reference electrode. Today's tDCS research rests on the conjecture that conclusions from research on healthy volunteers can guide translational research in clinical samples. However, in the case of the impact of tDCS on the attentional networks, this conjecture remains to be empirically tested. For instance, although the placement of both the anode over the left dlPFC and the reference electrode (i.e., cathode) over the contralateral supraorbital area has been proved to be useful in the improvement of the executive conflict network of attention via tDCS in healthy samples (e.g., Miler et al., 2017), others have suggested that positioning the anode over the left dlPFC and the cathode outside the scalp (e.g., deltoid, ipsilateral arm) could be beneficial in patients with comorbid anxiety and mood disorders (Nasiri et al., 2020). However, this issue has never been explored for cognitive tasks—such as the one used in

this project—and thus deserves a careful audit in future research.

Third, alike our discussion regarding the cathode placement, one may wonder whether (sub)clinical and healthy volunteers likewise benefit from the same anode placement. For instance, although the left dlPFC has been identified as a relevant target across distinct neurologic and psychiatric disorders (e.g., Brunoni & Vanderhasselt, 2014; Kekic et al., 2016; Mondino et al., 2014; Tortella et al., 2015), the ideal target regions to boost the attentional networks are far much less apparent in nonclinical samples. For instance, left hemispheric structures may, in the first place, not have similar involvement in attentional performance as the right parietal cortex among healthy volunteers who do not exhibit impoverished left PFC activations when completing tasks that involve the recruitment of attentional resources (e.g., Corbetta & Shulman, 2002; Lückmann et al., 2014). Targeting the left dlPFC in a nonclinical sample might thus be less than ideal as this region may not have sufficient influence to modulate attention functions in a nonclinical group. Recent evidence indicated that applying anodal tDCS over the right posterior parietal may modulate the attentional networks (e.g., Lo et al., 2019). Although our study was not designed to examine this question, a critical step in future research would thus be to determine whether clinical and nonclinical samples differ in terms of the brain regions that should be placed under the anode to modulate the executive conflict network of attention via tDCS. If that hypothesis were correct, it would clearly explain why we had observed the emergence of a beneficial effect of tDCS only when considering trait anxiety and depression symptomatology.

The present study may have implications. Indeed, we situate this preclinical study within the field's ongoing bench-to-bedside effort. One goal of preclinical research is to set the scene for novel clinical research directions. Because the present findings suggest that anodal tDCS over the left dlPFC may improve the efficiency of the executive conflict network of attention only when one's depressive symptomatology and trait anxiety are high, our findings invite the hypothesis that anodal tDCS may constitute a viable tool to improve impairments in the executive conflict network of attention among patients with depression or trait anxiety. Future research could also examine whether the improvement of the executive conflict network of attention via tDCS will generate a beneficial cascade of downstream benefits vis-à-vis depression and anxiety symptoms. As anxiety and depressive symptoms often covary (e.g., Brown et al., 2001; Kessler et al., 2005), our study also invites future research among patients with comorbid depression and anxiety disorders. And, lastly, given that impairments in the executive control of attention are assumed to play a role in the maintenance of a wide range of neuropsychiatric disorders (e.g., Araneda et al., 2015; Heeren et al., 2014; Maurage et al., 2014; Rochat et al., 2019; Woud et al. 2019), future research may also benefit from transcending current disorder-oriented nomenclature (e.g., Hayes & Hofmann, 2018; Mansell et al., 2009; Nolen-Hoeksema & Watkins, 2011) and restrict their recruitment to patients with impairments in the executive conflict network of attention, regardless of the psychiatric diagnosis.

Finally, our study has limitations that require further investigation in follow-up research. First, following previous research (e.g., Coussement et al., 2019; Miler et al., 2017; Roy et al., 2015), our participants were from an unselected community sample. However, our sample was heterogeneous, with 16% of participants reporting a total score above 14 at the BDI-II (the cut-off score for mild depression; Beck et al., 1998), 50% of participants reporting a total score above 40 at the STAI-T (the cut-off score for elevated trait anxiety; Julian, 2011), and 22 % of participants reporting a total score above 56 at the LSAS (the cut-off score for SAD for the French version; Heeren et al., 2012); thus, enabling us to avoid potential problems of restricted range variability that are common in healthy volunteers or in severe clinical samples (e.g., Terluin et al., 2016; Salkind, 2010). Nevertheless, future iterations would want to consider the impact of tDCS on the executive conflict network of attention at varying points in the development and course of depression, anxiety disorders, and their co-occurrence.

Second, we assessed the impact of anodal tDCS on the attentional networks during the stimulation (i.e., online), but did not collect post-stimulation data (i.e., offline). On the other hand, research has so far never reported any beneficial effect of tDCS on the executive conflict network of attention when this latter was assessed offline and without the completion of a cognitively-demanding task during the stimulation (e.g., Coffman et al., 2012; Lo et al., 2019; Roy et al., 2015). An offline administration of the ANT would thus require deciding which task should be administered online, in combination with the anodal tDCS. So far, only one study (Silva et al., 2017) has examined this issue and suggest that combining a go/nogo task (that is, online) to the anodal tDCS may yield post-stimulation (i.e., offline) beneficial impacts on both the orienting and the executive conflict networks. Future studies should further investigate whether trait anxiety and depressive symptoms also drive offline ANT's tDCS-induced effects. However, offline and persistent improvements often require repeated tDCS sessions (e.g., Nissim et al., 2019, but see Mosayebi Samani et al., 2020).

Third, we used a 35-cm2 electrode's size. However, although this size has been proved to be optimal in terms of cortical excitability (e.g., Ho et al., 2016), it might be less than ideal in terms of focality (e.g., Bastani & Jaberzadeh, 2013; Imburgio & Orr, 2018). Future iterations would thus want to examine whether the present findings replicate with a more focal stimulation (e.g., 16cm2 electrodes). This issue is especially relevant given that a beneficial impact of anodal tDCS on the executive conflict network of attention has been found in a study relying on smaller electrode's sizes (i.e., 16cm2; Miler et al., 2017)[1].

Fourth, trait anxiety and depression do share common features that might have driven the effects of tDCS. For instance, intrusive thoughts and difficulty disengaging attention from negative concerns have been identified as central features of trait anxiety and depression (e.g., De Raedt & Koster, 2010; Clark & de Silva, 1985; Heeren et al., 2018). And, interestingly, they both have been repeatedly associated with features of the executive conflict network of attention (e.g., Bomyea, & Amir, 2011; Reinholdt-Dunne et al., 2009; Taylor et al., 2016; Verwoerd et al., 2008; Woud et al., 2019). As such, one cannot rule out the hypothesis that the mechanisms at play here are neither trait anxiety nor depression per se but rather the transdiagnostic processes that are shared between features of depression and trait anxiety. Future research would thus want to dispense with broad and somewhat vague clinical entities and examine whether the baseline's magnitude of transdiagnostic processes (for discussion, see Hayes & Hofmann, 2018; Mansell et al., 2009; Nolen-Hoeksema & Watkins, 2011) may boost the impact of tDCS on the attentional networks.

[1] We are thankful to one of the anonymous reviewers of this paper for drawing our attention to this point.

Finally, this study's purpose required the use of a group-level approach that does not always generalize to idiographic, within-individual approach that is requisite for the clinical recommendations for a specific patient (Fisher et al., 2018). Further exploration of the impacts of tDCS on the attentional networks via exhaustive idiographic approach to individual participants may ultimately be a more appropriate approach for clinical practice (for example in other contexts, see Billieux et al., 2015; Philippot et al., 2019). Bayesian case-control research methods might also help achieve this aim (e.g., Heeren, Busana et al., 2015).

In conclusion, the present study is not definitive, but it highlights the value of considering depression and trait anxiety when thinking about the impact of anodal tDCS on the executive conflict network of attention. Like other preclinical laboratory studies, this study fulfills a valuable niche, wherein preclinical data provide critical clues for larger, more definitive future translational efforts.

References

Araneda, R., De Volder, A. G., Deggouj, N., Philippot, P., Heeren, A., Lacroix, E., Decat, M., Rombaux, P., & Renier, L. (2015). Altered top-down cognitive control and auditory processing in tinnitus: Evidences from auditory and visual spatial stroop. *Restorative neurology and neuroscience*, *33*(1), 67–80. https://doi.org/10.3233/RNN-140433

Ayache, S. S., Palm, U., Chalah, M. A., Al-Ani, T., Brignol, A., Abdellaoui, M., Dimitri, D., Sorel, M., Créange, A., & Lefaucheur, J.-P. (2016). Prefrontal tDCS Decreases Pain in Patients with Multiple Sclerosis. *Frontiers in Neuroscience*, *10*, 147. https://doi.org/10.3389/fnins.2016.00147

Bas-Hoogendam, J. M., & Westenberg, P. M. (2020). Imaging the socially-anxious brain: Recent advances and future prospects. *F1000Research*, *9*. https://doi.org/10.12688/f1000research.21214.1

Bastani, A., & Jaberzadeh, S. (2013). a-tDCS Differential Modulation of Corticospinal Excitability : The Effects of Electrode Size. *Brain Stimulation*, *6*(6), 932-937. https://doi.org/10.1016/j.brs.2013.04.005

Beck, A. T., Steer, R. A., & Brown, G. K. (1998). *Inventaire de Dépression de Beck—2ème édition (IDB-II) [Beck Depression Inventory—2nd edition (BDI-II)]* (Editions du Centre de Psychologie Appliquée).

Bellaera, L., & von Mühlenen, A. (2017). The effect of induced sadness and moderate depression on attention networks. *Cognition & Emotion*, *31*(6), 1140–1152. https://doi.org/10.1080/02699931.2016.1197101

Benjamini, Y., & Hochberg, Y. (1995). Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. *Journal of the Royal Statistical Society. Series B (Methodological)*, *57*(1), 289-300. https://doi.org/0035-9246/95/57289

Bikson, M., Datta, A., Rahman, A., & Scaturro, J. (2010). Electrode montages for tDCS and weak transcranial electrical stimulation: Role of "return" electrode's position and size. *Clinical Neurophysiology*, *121*(12), 1976-1978. https://doi.org/10.1016/j.clinph.2010.05.020

Billieux, J., Philippot, P., Schmid, C., Maurage, P., De Mol, J., & Van der Linden, M. (2015). Is Dysfunctional Use of the Mobile Phone a Behavioural Addiction? Confronting Symptom-Based Versus Process-Based Approaches. *Clinical psychology & psychotherapy*, *22*(5), 460–468. https://doi.org/10.1002/cpp.1910

Bishop, S. J. (2009). Trait anxiety and impoverished prefrontal control of attention. *Nature Neuroscience*, *12*(1), 92-98. https://doi.org/10.1038/nn.2242

Bomyea, J., & Amir, N. (2011). The Effect of an Executive Functioning Training Program on Working Memory Capacity and Intrusive Thoughts. *Cognitive therapy and research*, *35*(6), 529-535. https://doi.org/10.1007/s10608-011-9369-8

Brown, T. A., Campbell, L. A., Lehman, C. L., Grisham, J. R., & Mancill, R. B. (2001). Current and lifetime comorbidity of the DSM-IV anxiety and mood disorders in a large clinical sample. *Journal of Abnormal Psychology*, *110*(4), 585-599. https://doi.org/10.1037/0021-843X.110.4.585

Bruchon-Schweitzer, M., & Paulhan, I. (1993). *Adaptation francophone de l'inventaire d'anxiete Trait-Etat (Forme Y) de Spielberger.* (Editions du Centre Psychologie Appliquée).

Brühl, A. B., Hänggi, J., Baur, V., Rufer, M., Delsignore, A., Weidt, S., Jäncke, L., & Herwig, U. (2014). Increased cortical thickness in a frontoparietal network in social anxiety disorder: Increased Cortical Thickness in SAD. *Human Brain Mapping*, *35*(7), 2966-2977. https://doi.org/10.1002/hbm.22378

Brunoni, A. R., Nitsche, M. A., Bolognini, N., Bikson, M., Wagner, T., Merabet, L., Edwards, D. J., Valero-Cabre, A., Rotenberg, A., Pascual-Leone, A., Ferrucci, R., Priori, A., Boggio, P. S., & Fregni, F. (2012). Clinical research with transcranial direct current stimulation (tDCS): Challenges and future directions. *Brain Stimulation*, *5*(3), 175-195. https://doi.org/10.1016/j.brs.2011.03.002

Brunoni, A. R., & Vanderhasselt, M.-A. (2014). Working memory improvement with non-invasive brain stimulation of the dorsolateral prefrontal cortex: A systematic review and meta-analysis. *Brain and Cognition*, *86*, 1-9. https://doi.org/10.1016/j.bandc.2014.01.008

Chalah, M. A., Riachi, N., Ahdab, R., Mhalla, A., Abdellaoui, M., Créange, A., Lefaucheur, J. P., & Ayache, S. S. (2017). Effects of left DLPFC versus right PPC tDCS on multiple sclerosis fatigue. *Journal of the neurological sciences*, *372*, 131–137. https://doi.org/10.1016/j.jns.2016.11.015

Clark, D. A., & de Silva, P. (1985). The nature of depressive and anxious, intrusive thoughts: Distinct or uniform phenomena? *Behaviour Research and Therapy*, *23*(4), 383-393. https://doi.org/10.1016/0005-7967(85)90166-4

Coffman, B. A., Trumbo, M. C., & Clark, V. P. (2012). Enhancement of object detection with transcranial direct current stimulation is associated with increased attention. *BMC neuroscience*, *13*, 108. https://doi.org/10.1186/1471-2202-13-108

Cogiamanian, F., Marceglia, S., Ardolino, G., Barbieri, S., & Priori, A. (2007). Improved isometric force endurance after transcranial direct current stimulation over the human motor cortical areas. *The European Journal of Neuroscience*, *26*(1), 242-249. https://doi.org/10.1111/j.1460-9568.2007.05633.x

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience*, *3*(3), 201-215. https://doi.org/10.1038/nrn755

Coussement, C., Maurage, P., Billieux, J., & Heeren, A. (2019). Does Change in Attention Control Mediate the Impact of tDCS on Attentional Bias for Threat? Limited Evidence from a Double-blind Sham-controlled Experiment in an Unselected Sample. *Psychologica Belgica*, *59*(1), 16-32. https://doi.org/10.5334/pb.449

DaSilva, A. F., Volz, M. S., Bikson, M., & Fregni, F. (2011). Electrode positioning and montage in transcranial direct current stimulation. *Journal of Visualized Experiments: JoVE*, *51*. https://doi.org/10.3791/2744

De Raedt, R., & Koster, E. H. W. (2010). Understanding vulnerability for depression from a cognitive neuroscience perspective: A reappraisal of attentional factors and a new conceptual framework. *Cognitive, Affective, & Behavioral Neuroscience*, *10*(1), 50-70. https://doi.org/10.3758/

CABN.10.1.50

Dedoncker, J., Brunoni, A. R., Baeken, C., & Vanderhasselt, M.-A. (2016). A Systematic Review and Meta-Analysis of the Effects of Transcranial Direct Current Stimulation (tDCS) Over the Dorsolateral Prefrontal Cortex in Healthy and Neuropsychiatric Samples: Influence of Stimulation Parameters. *Brain Stimulation*, *9*(4), 501-517. https://doi.org/10.1016/j.brs.2016.04.006

DeJong, H., Fox, E., & Stein, A. (2019). Does rumination mediate the relationship between attentional control and symptoms of depression? *Journal of Behavior Therapy and Experimental Psychiatry*, *63*, 28-35. https://doi.org/10.1016/j.jbtep.2018.12.007

Fan, J., McCandliss, B. D., Fossella, J., Flombaum, J. I., & Posner, M. I. (2005). The activation of attentional networks. *NeuroImage*, *26*(2), 471-479. https://doi.org/10.1016/j.neuroimage.2005.02.004

Fan, J., McCandliss, B. D., Sommer, T., Raz, A., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience*, *14*(3), 340-347. https://doi.org/10.1162/089892902317361886

Ferrucci, R., Bortolomasi, M., Vergari, M., Tadini, L., Salvoro, B., Giacopuzzi, M., Barbieri, S., & Priori, A. (2009). Transcranial direct current stimulation in severe, drug-resistant major depression. *Journal of Affective Disorders*, *118*(1-3), 215-219. https://doi.org/10.1016/j.jad.2009.02.015

Fisher, A. J., Medaglia, J. D., & Jeronimus, B. F. (2018). Lack of group-to-individual generalizability is a threat to human subjects research. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(27), E6106-E6115. https://doi.org/10.1073/pnas.1711978115

Fregni, F., Boggio, P. S., Nitsche, M., Bermpohl, F., Antal, A., Feredoes, E., Marcolin, M. A., Rigonatti, S. P., Silva, M. T. A., Paulus, W., & Pascual-Leone, A. (2005). Anodal transcranial direct current stimulation of prefrontal cortex enhances working memory. *Experimental Brain Research*, *166*(1), 23-30. https://doi.org/10.1007/s00221-005-2334-6

Fregni, F., & Pascual-Leone, A. (2007). Technology Insight: Noninvasive brain stimulation in neurology—perspectives on the therapeutic potential of rTMS and tDCS. *Nature Clinical Practice Neurology*, *3*(7), 383-393. https://doi.org/10.1038/ncpneuro0530

Grafton, B., MacLeod, C., Rudaizky, D., Holmes, E. A., Salemink, E., Fox, E., & Notebaert, L. (2017). Confusing procedures with process when appraising the impact of cognitive bias modification on emotional vulnerability. *The British journal of psychiatry: the journal of mental science*, *211*(5), 266–271. https://doi.org/10.1192/bjp.bp.115.176123

Hammar, Å., & Årdal, G. (2009). Cognitive Functioning in Major Depression – A Summary. *Frontiers in Human Neuroscience*, *3*, 26. https://doi.org/10.3389/neuro.09.026.2009

Hare, B. D., & Duman, R. S. (2020). Prefrontal cortex circuits in depression and anxiety: Contribution of discrete neuronal populations and target regions. *Molecular Psychiatry*, 1-17. https://doi.org/10.1038/s41380-020-0685-9

Hayes, S. C., & Hofmann, S. G. (2018). *Process-Based CBT: The Science and Core Clinical Competencies of Cognitive Behavioral Therapy*. New Harbinger Publications.

Heeren, A., Bernstein, E., & McNally, R. J. (2018). Deconstructing trait anxiety: A network perspective. *Anxiety, Stress, & Coping*, *31*(3), 262-276. https://doi.org/10.1080/10615806.2018.1439263

Heeren, A., Billieux, J., Philippot, P., De Raedt, R., Baeken, C., de Timary, P., Maurage, P., & Vanderhasselt, M.-A. (2017). Impact of transcranial direct current stimulation on attentional bias for threat: A proof-of-concept study among individuals with social anxiety disorder. *Social, Cognitive, and Affective Neuroscience*, *21*, 251-260. https://doi.org/10.1093/scan/nsw119

Heeren, A., Billieux, J., Philippot, P., & Maurage, P. (2015). Looking under the hood of executive function impairments in psychopathology: A commentary on "Advancing understanding of executive function impairments and psychopathology: bridging the gap between clinical and cognitive approaches". *Frontiers in Psychology*, *6*, 1170. https://doi.org/10.3389/fpsyg.2015.01170

Heeren, A., Busana, C., Coussement, C., & Philippot, P. (2015). Mindfulness-Based Cognitive Therapy for Trichotillomania: A Bayesian Case-Control Study. *Psychologica Belgica*, *55*(3), 118-133. https://doi.org/10.5334/pb.bj

Heeren, A., De Raedt, R., Koster, E. H. W., & Philippot, P. (2013). The (neuro)cognitive mechanisms behind attention bias modification in anxiety: Proposals based on theoretical accounts of attentional bias. *Frontiers in Human Neuroscience*, *7*, 119. https://doi.org/10.3389/fnhum.2013.00119

Heeren, A., Dricot, L., Billieux, J., Philippot, P., Grynberg, D., de Timary, P., & Maurage, P. (2017). Correlates of Social Exclusion in Social Anxiety Disorder: An fMRI study. *Scientific Reports*, *7*(1), 260. https://doi.org/10.1038/s41598-017-00310-9

Heeren, A., Hoebeke, Y., & Coussement, C. (2019). Unfolding the complex dynamic interplay between attentional processes and anxiety: A commentary on Ghassemzadeh, Rothbart, and Posner. *Cognitive and Behavioral Neurology, 32*(1), 63–66. https://doi.org/10.1097/WNN.0000000000000187

Heeren, A., Maurage, P., Perrot, H., De Volder, A., Renier, L., Araneda, R., Lacroix, E., Decat, M., Deggouj, N., & Philippot, P. (2014). Tinnitus specifically alters the top-down executive control sub-component of attention: Evidence from the Attention Network Task. *Behavioural Brain Research*, *269*, 147-154. https://doi.org/10.1016/j.bbr.2014.04.043

Heeren, A., Maurage, P., & Philippot, P. (2015). Revisiting attentional processing of non-emotional cues in social anxiety: A specific impairment for the orienting network of attention. *Psychiatry Research*, *228*(1), 136-142. https://doi.org/10.1016/j.psychres.2015.04.030

Heeren, A., Maurage, P., Rossignol, M., Vanhaelen, M., Peschard, V., & Eeckhout, C. (2012). The self-report version of the Liebowitz social anxiety scale: Psychometric properties of the French version. *Canadian Journal of Behavioural Science*, *44*(2), 99-107. https://doi.org/10.1037/a0026249

Heeren, A., & McNally, R. J. (2016). An integrative network approach to social anxiety disorder: The complex dynamic interplay among attentional bias for threat, attentional control, and symptoms. *Journal of Anxiety Disorders*, *42*, 95-104. https://doi.org/10.1016/j.janxdis.2016.06.009

Heeren, A., Mogoaşe, C., McNally, R. J., Schmitz, A., & Philippot, P. (2015). Does attention bias modification improve attentional control? A double-blind randomized experiment with individuals with social anxiety disorder. *Journal of Anxiety Disorders*, *29*, 35-42. https://doi.org/10.1016/j.janxdis.2014.10.007

Heeren, A., Philippot, P., & Koster, E. H. W. (2015). Impact of the temporal stability of preexistent attentional bias for threat on its alteration through attention bias modification. *Journal of Behavior Therapy and Experimental Psychiatry*, *49*, 69-75. https://doi.org/10.1016/j.jbtep.2014.10.012

Hill, A. T., Fitzgerald, P. B., & Hoy, K. E. (2016). Effects of Anodal Transcranial Direct Current Stimulation on Working Memory: A Systematic Review and Meta-Analysis of Findings From Healthy and Neuropsychiatric

Populations. *Brain Stimulation*, *9*(2), 197-208. https://doi.org/10.1016/j.brs.2015.10.006

Ho, K.-A., Taylor, J. L., Chew, T., Gálvez, V., Alonzo, A., Bai, S., Dokos, S., & Loo, C. K. (2016). The Effect of Transcranial Direct Current Stimulation (tDCS) Electrode Size and Current Intensity on Motor Cortical Excitability : Evidence From Single and Repeated Sessions. *Brain Stimulation*, *9*(1), 1-7. https://doi.org/10.1016/j.brs.2015.08.003

Horvath, J. C., Forte, J. D., & Carter, O. (2015). Quantitative review finds No evidence of cognitive effects in healthy populations from single-session transcranial direct current stimulation (tDCS). Brain Stimulation, 8(3), 535e550. http://dx.doi.org/ 10.1016/j.brs.2015.01.400.

Hu, B., Rao, J., Li, X., Cao, T., Li, J., Majoe, D., & Gutknecht, J. (2017). Emotion Regulating Attentional Control Abnormalities in Major Depressive Disorder: An Event-Related Potential Study. *Scientific Reports*, *7*, 13530. https://doi.org/10.1038/s41598-017-13626-3

Imburgio, M. J., & Orr, J. M. (2018). Effects of prefrontal tDCS on executive function: Methodological considerations revealed by meta-analysis. *Neuropsychologia*, *117*, 156-166. https://doi.org/10.1016/j.neuropsychologia.2018.04.022

Jha, A. P., Krompinger, J., & Baime, M. J. (2007). Mindfulness training modifies subsystems of attention. *Cognitive, Affective, & Behavioral Neuroscience*, *7*(2), 109-119. https://doi.org/10.3758/CABN.7.2.109

Julian, L. J. (2011). Measures of anxiety: State-Trait Anxiety Inventory (STAI), Beck Anxiety Inventory (BAI), and Hospital Anxiety and Depression Scale-Anxiety (HADS-A). *Arthritis Care & Research*, *63*(S11), S467-S472. https://doi.org/10.1002/acr.20561

Kekic, M., Boysen, E., Campbell, I. C., & Schmidt, U. (2016). A systematic review of the clinical efficacy of transcranial direct current stimulation (tDCS) in psychiatric disorders. *Journal of Psychiatric Research*, *74*, 70-86. https://doi.org/10.1016/j.jpsychires.2015.12.018

Kessler, R. C., Chiu, W. T., Demler, O., & Walters, E. E. (2005). Prevalence, Severity, and Comorbidity of 12-Month DSM-IV Disorders in the National Comorbidity Survey Replication. *Archives of General Psychiatry*, *62*, 617-627. https://doi.org/10.1001/archpsyc.62.6.617

Kuckertz, J. M., Gildebrant, E., Liliequist, B., Karlström, P., Väppling, C., Bodlund, O., Stenlund, T., Hofmann, S. G., Andersson, G., Amir, N., & Carlbring, P. (2014). Moderation and mediation of the effect of attention training in social anxiety disorder. *Behaviour Research and Therapy*, *53*, 30-40. https://doi.org/10.1016/j.brat.2013.12.003

Kwak, S., Kim, S.-Y., Bae, D., Hwang, W.-J., Cho, K. I. K., Lim, K.-O., Park, H.-Y., Lee, T. Y., & Kwon, J. S. (2020). Enhanced Attentional Network by Short-Term Intensive Meditation. *Frontiers in Psychology*, *10*, 3073. https://doi.org/10.3389/fpsyg.2019.03073

Lannoy, S., Heeren, A., Dormal, V., Billieux, J., & Maurage, P. (2019). Is there room for attentional impairments in binge drinking? A commentary on Carbia et al. (2018). *Neuroscience & Biobehavioral Reviews*, *98*, 58-60. https://doi.org/10.1016/j.neubiorev.2019.01.006

Lannoy, S., Heeren, A., Moyaerts, N., Bruneau, N., Evrard, S., Billieux, J., & Maurage, P. (2017). Differential impairments across attentional networks in binge drinking. *Psychopharmacology*, *234*(7), 1059-1068. https://doi.org/10.1007/s00213-017-4538-4

Liebowitz, M. R. (1987). Social phobia. *Modern Problems of Pharmacopsychiatry*, *22*, 141-173. https://doi.org/10.1159/000414022

Lo, O.-Y., van Donkelaar, P., & Chou, L.-S. (2019). Effects of transcranial direct current stimulation over right posterior parietal cortex on attention function in healthy young adults. *The European journal of neuroscience*, *49*(12), 1623-1631. https://doi.org/10.1111/ejn.14349

Lückmann, H. C., Jacobs, H. I. L., & Sack, A. T. (2014). The cross-functional role of frontoparietal regions in cognition: Internal attention as the overarching mechanism. *Progress in Neurobiology*, *116*, 66-86. https://doi.org/10.1016/j.pneurobio.2014.02.002

Mansell, W., Harvey, A., Watkins, E., & Shafran, R. (2009). Conceptual Foundations of the Transdiagnostic Approach to CBT. *Journal of Cognitive Psychotherapy*, *23*(1), 6-19. https://doi.org/10.1891/0889-8391.23.1.6

Maurage, P., de Timary, P., Billieux, J., Collignon, M., & Heeren, A. (2014). Attentional Alterations in Alcohol Dependence Are Underpinned by Specific Executive Control Deficits. *Alcoholism: Clinical and Experimental Research*, *38*(7), 2105-2112. https://doi.org/10.1111/acer.12444

Maurage, P., Heeren, A., Lahaye, M., Jeanjean, A., Guettat, L., Verellen-Dumoulin, C., Halkin, S., Billieux, J., & Constant, E. (2017). Attentional impairments in Huntington's disease: A specific deficit for the executive conflict. *Neuropsychology*, *31*(4), 424-436. https://doi.org/10.1037/neu0000321

Medina, J., & Cason, S. (2017). No evidential value in samples of transcranial direct current stimulation (tDCS) studies of cognition and working memory in healthy populations. *Cortex*, *94*, 131–141. https://doi.org/10.1016/j.cortex.2017.06.021

Miler, J. A., Meron, D., Baldwin, D. S., & Garner, M. (2017). The Effect of Prefrontal Transcranial Direct Current Stimulation on Attention Network Function in Healthy Volunteers: TDCS and Attention Network Function. *Neuromodulation: Technology at the Neural Interface*, *21*(4), 355-361. https://doi.org/10.1111/ner.12629

Mogoaşe, C., David, D., & Koster, E. H. W. (2014). Clinical Efficacy of Attentional Bias Modification Procedures: An Updated Meta-Analysis: Clinical Efficacy of Attention Retraining. *Journal of Clinical Psychology*, *70*(12), 1133-1157. https://doi.org/10.1002/jclp.22081

Moliadze, V., Antal, A., & Paulus, W. (2010). Electrode-distance dependent after-effects of transcranial direct and random noise stimulation with extracephalic reference electrodes. *Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology*, *121*(12), 2165-2171. https://doi.org/10.1016/j.clinph.2010.04.033

Mondino, M., Bennabi, D., Poulet, E., Galvao, F., Brunelin, J., & Haffen, E. (2014). Can transcranial direct current stimulation (tDCS) alleviate symptoms and improve cognition in psychiatric disorders? *The World Journal of Biological Psychiatry*, *15*(4), 261-275. https://doi.org/10.3109/15622975.2013.876514

Moriya, J., & Tanno, Y. (2009). Dysfunction of attentional networks for non-emotional processing in negative affect. *Cognition and Emotion*, *23*(6), 1090-1105. https://doi.org/10.1080/02699930802335018

Mosayebi Samani, M., Agboada, D., Kuo, M. F., & Nitsche, M. A. (2020). Probing the relevance of repeated cathodal transcranial direct current stimulation over the primary motor cortex for prolongation of after-effects. *The Journal of physiology*, *598*(4), 805–816. https://doi.org/10.1113/JP278857

Nissim, N. R., O'Shea, A., Indahlastari, A., Kraft, J. N., von Mering, O., Aksu, S., Porges, E., Cohen, R., & Woods, A. J. (2019). Effects of transcranial direct current stimulation paired with cognitive training on functional connectivity of the working memory network in older adults. *Frontiers in Aging Neuroscience*, *11*, 340. https://doi.org/10.3389/fnagi.2019.00340

Nitsche, M. A., Cohen, L. G., Wassermann, E. M., Priori, A., Lang, N., Antal, A., Paulus, W., Hummel, F., Boggio, P.

S., Fregni, F., & Pascual-Leone, A. (2008). Transcranial direct current stimulation: State of the art 2008. *Brain Stimulation*, *1*(3), 206-223. https://doi.org/10.1016/j.brs.2008.06.004

Nitsche, M. A., & Paulus, W. (2000). Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. *The Journal of Physiology*, *527*(3), 633-639. https://doi.org/10.1111/j.1469-7793.2000.t01-1-00633.x

Nitsche, M. A., & Paulus, W. (2001). Sustained excitability elevations induced by transcranial DC motor cortex stimulation in humans. *Neurology*, *57*(10), 1899-1901. https://doi.org/10.1212/WNL.57.10.1899

Nolen-Hoeksema, S., & Watkins, E. R. (2011). A Heuristic for Developing Transdiagnostic Models of Psychopathology: Explaining Multifinality and Divergent Trajectories. *Perspectives on Psychological Science*, *6*(6), 589-609. https://doi.org/10.1177/1745691611419672

Ohn, S. H., Park, C.-I., Yoo, W.-K., Ko, M.-H., Choi, K. P., Kim, G.-M., Lee, Y. T., & Kim, Y.-H. (2008). Time-dependent effect of transcranial direct current stimulation on the enhancement of working memory. *Neuroreport*, *19*(1), 43-47. https://doi.org/10.1097/WNR.0b013e3282f2adfd

Pacheco-Unguetti, A. P., Acosta, A., Marqués, E., & Lupiáñez, J. (2011). Alterations of the attentional networks in patients with anxiety disorders. *Journal of Anxiety Disorders*, *25*(7), 888-895. https://doi.org/10.1016/j.janxdis.2011.04.010

Petersen, S. E., & Posner, M. I. (2012). The Attention System of the Human Brain: 20 Years After. *Annual review of neuroscience*, *35*, 73-89. https://doi.org/10.1146/annurev-neuro-062111-150525

Philippot, P., Bouvard, M., Baeyens, C., & Dethier, V. (2019). Case conceptualization from a process-based and modular perspective: Rationale and application to mood and anxiety disorders. *Clinical Psychology & Psychotherapy*, *26*(2), 175-190. https://doi.org/10.1002/cpp.2340

Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience*, *13*, 25-42. https://doi.org/10.1146/annurev.ne.13.030190.000325

Posner, M. I., & Rothbart, M. K. (2007). Research on Attention Networks as a Model for the Integration of Psychological Science. *Annual Review of Psychology*, *58*(1), 1-23. https://doi.org/10.1146/annurev.psych.58.110405.085516

Posner, M. I., Rothbart, M. K., & Ghassemzadeh, H. (2019). Restoring Attention Networks. *The Yale Journal of Biology and Medicine*, *92*(1), 139-143.

Priori, A., Mameli, F., Cogiamanian, F., Marceglia, S., Tiriticco, M., Mrakic-Sposta, S., Ferrucci, R., Zago, S., Polezzi, D., & Sartori, G. (2008). Lie-Specific Involvement of Dorsolateral Prefrontal Cortex in Deception. *Cerebral Cortex*, *18*(2), 451-455. https://doi.org/10.1093/cercor/bhm088

Reinholdt-Dunne, M. L., Mogg, K., & Bradley, B. P. (2009). Effects of anxiety and attention control on processing pictorial and linguistic emotional information. *Behaviour Research and Therapy*, *47*(5), 410-417. https://doi.org/10.1016/j.brat.2009.01.012

Rochat, L., Maurage, P., Heeren, A., & Billieux, J. (2019). Let's Open the Decision-Making Umbrella: A Framework for Conceptualizing and Assessing Features of Impaired Decision Making in Addiction. *Neuropsychology Review*, *29*(1), 27-51. https://doi.org/10.1007/s11065-018-9387-3

Roy, L. B., Sparing, R., Fink, G. R., & Hesse, M. D. (2015). Modulation of attention functions by anodal tDCS on right PPC. *Neuropsychologia*, *74*, 96-107. https://doi.org/10.1016/j.neuropsychologia.2015.02.028

Salkind, N. J. (2010). *Encyclopedia of research design* (Vols. 1-0). Thousand Oaks, CA: SAGE Publications, Inc. http://dx.doi.org/10.4135/9781412961288

Silva, A. F., Zortea, M., Carvalho, S., Leite, J., Torres, I. L. da S., Fregni, F., & Caumo, W. (2017). Anodal transcranial direct current stimulation over the left dorsolateral prefrontal cortex modulates attention and pain in fibromyalgia: Randomized clinical trial. *Scientific Reports*, *7*(1), 135. https://doi.org/10.1038/s41598-017-00185-w

Spielberger, C. D., Gorsuch, R. L., Lushene, R., Vagg, P. R., & Jacobs, G. (1983). *Manual for the state-trait anxiety inventory.* (Consulting Psychologists Press).

Taylor, C. T., Cross, K., & Amir, N. (2016). Attentional control moderates the relationship between social anxiety symptoms and attentional disengagement from threatening information. *Journal of Behavior Therapy and Experimental Psychiatry*, *50*, 68-76. https://doi.org/10.1016/j.jbtep.2015.05.008

Terluin, B., de Boer, M. R., & de Vet, H. C. W. (2016). Differences in Connection Strength between Mental Symptoms Might Be Explained by Differences in Variance: Reanalysis of Network Data Did Not Confirm Staging. *PLoS one*, *11*(11), e0155205. https://doi.org/10.1371/journal.pone.0155205

Togo, F., Lange, G., Natelson, B. H., & Quigley, K. S. (2015). Attention network test: assessment of cognitive function in chronic fatigue syndrome. *Journal of neuropsychology*, *9*(1), 1–9. https://doi.org/10.1111/jnp.12030

Tortella, G., Casati, R., Aparicio, L. V. M., Mantovani, A., Senço, N., D'Urso, G., Brunelin, J., Guarienti, F., Selingardi, P. M. L., Muszkat, D., Junior, B. de S. P., Valiengo, L., Moffa, A. H., Simis, M., Borrione, L., & Brunoni, A. R. (2015). Transcranial direct current stimulation in psychiatric disorders. *World Journal of Psychiatry*, *5*(1), 88-102. https://doi.org/10.5498/wjp.v5.i1.88

Tortella-Feliu, M., Morillas-Romero, A., Balle, M., Bornas, X., Llabrés, J., & Pacheco-Unguetti, A. P. (2014). Attentional control, attentional network functioning, and emotion regulation styles. *Cognition and Emotion*, *28*(5), 769-780. https://doi.org/10.1080/02699931.2013.860889

Trumbo, M. C., Coffman, B. A., & Clark, V. P. (2014). The effect of transcranial direct current stimulation (tDCS) on the attention network task (ANT) : Contextualizing prior research. *Brain Stimulation: Basic, Translational, and Clinical Research in Neuromodulation*, *7*(2), 8. https://doi.org/10.1016/j.brs.2014.01.030

Verwoerd, J., de Jong, P.J. & Wessel, I. (2008). Low Attentional Control and the Development of Intrusive Memories Following a Laboratory Stressor. *Journal of Psychopathology and Behavioral Assess*ment, 30**,** 291–297. https://doi.org/10.1007/s10862-008-9080-6

Wang, L., LaBar, K. S., Smoski, M., Rosenthal, M. Z., Dolcos, F., Lynch, T. R., Krishnan, R. R., & McCarthy, G. (2008). Prefrontal mechanisms for executive control over emotional distraction are altered in major depression. *Psychiatry research*, *163*(2), 143-155. https://doi.org/10.1016/j.pscychresns.2007.10.004

Wang, H., Mo, C., & Fang, F. (2020). Dissociated deficits in attentional networks in social anxiety and depression. *Science China. Life Sciences*, *63*, 1071–1078. https://doi.org/10.1007/s11427-019-1624-5

Woud, M. L., Heeren, A., Shkreli, L., Meyer, T., Egeri, L., Cwik, J. C., Zlomuzica, A., Kessler, H., & Margraf, J. (2019). Investigating the effect of proactive interference control training on intrusive memories. *European Journal of Psychotraumatology*, *10*(1), 1611092. https://doi.org/10.1080/20008198.2019.1611092