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Reduction of implicit cognitive bias with cathodal tDCS to the left prefrontal cortex

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Abstract

Implicit associations can interfere with cognitive operations and behavioral decisions without direct intention. Enhancement of neural activity with anodal transcranial direct current stimulation (tDCS) was proposed to reduce implicit associations by means of improved cognitive control. However, a targeted reduction of distractive implicit associations by inhibitory cathodal tDCS, recently shown in spatial–numerical associations, provides an interesting alternative approach to support goal-directed behavior with transcranial brain stimulation. To test this rationale with a sham-controlled cross-over design, a standardized Implicit Association Test (IAT) was performed by 24 healthy participants parallel to 1 mA cathodal or sham tDCS to the left prefrontal cortex. In this double-classification task, *insect* versus *flower* pictures and *negative* versus *positive* words are mapped together onto two shared response keys with crossed response assignments in separate blocks. Responses were faster when *insect* + *negative* and *flower* + *positive* stimuli required the same answer (IAT effect). Most critically, the IAT effect was reduced during cathodal tDCS as compared to sham stimulation. Thus, results are consistent with the proposed stimulation rationale, with previous observations, and complementary to previous studies using different tDCS configurations.

Keywords transcranial Direct Current Stimulation · Cathodal tDCS · Implicit associations · IAT · Prefrontal cortex

Human behavior does not always reflect goal-directed deliberate choice. Instead, and particularly in demanding situations with little cognitive resources, spontaneous decisions can be based on implicit associations. The emergence of implicit associations is often neither consciously intended, directly perceived, nor convergent to explicit self-reports (Greenwald, Mcghee, & Schwartz, 1998). Nevertheless, indirect measurements of implicit associations can predict related behaviors incremental to explicit self-report measures (Greenwald, Poehlman, Uhlmann, & Banaji, 2009). For example, addictive and obesogenic behaviors are informed by implicit processes which are thus taken to moderate maladaptive choices in the long run (De Houwer, 2002; Hofmann, Rauch, & Gawronski, 2007; Huijding, De Jong, Wiers, & Verkooijen, 2005; Wiers, Van Woerden, Smulders, & De Jong, 2002), although the diagnostic criteria (validity and reliability) and underlying mechanisms of different measurements are still controversial (Fiedler, Messner, & Bluemke, 2006). Implicit associations were also shown in critical (anti-) social behaviors such as stereotyping, pedophilia, or psychopathology (Gawronski & De Houwer, 2014; Gray, Brown, MacCulloch, Smith, & Snowden, 2005; Greenwald et al., 1998, Experiment 3; Roefs et al., 2011). Interventions that reduce the impact of implicit associations on behavior could facilitate a more deliberate cognitive processing, and we here hypothesized the left prefrontal cortex to host activation of implicit biases in verbal processing.

External modulation of prefrontal cortical areas by application of transcranial direct current stimulation (tDCS) was already proposed and investigated as a possibility to change

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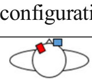
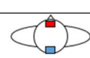
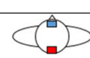
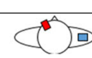
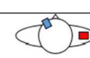
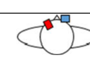
implicit associations in healthy and patient populations (see Table 1). In tDCS, a weak direct current is sent through brain tissue between two electrode pads. Resting membrane potentials are slightly modulated with strongest effects in dense electric fields under the pad electrodes dependent on the current inward or outward direction (Nitsche & Paulus, 2000) and on the individual neuron orientation (Radman, Ramos, Brumberg, &, Bikson, 2009). The rationale of previous studies on implicit associations was to enhance higher-order regulation processes (e.g., cognitive control) by increasing firing rates in prefrontal areas, in accordance with neuroimaging correlates (Chee, Sriram, Soon, & Lee, 2000) and active interference of PFC activity with transcranial magnetic stimulation (Cattaneo, Mattavelli, Platania, & Papagno, 2011; Crescentini, Aglioti, Fabbro, & Urgesi, 2014). Consistent with this concept, anodal tDCS of the medial PFC led to smaller effects in a study testing implicit racial biases (Sellaro et al., 2015). More precisely, using an Implicit Association Test (IAT), implicit racial biases were indirectly confirmed by faster response latencies for shared responses on in-group names paired with positive words and out-group names paired with negative word evaluations, than for the crossed task assignments. The results of Sellaro et al. (2015) further showed smaller differences between these congruent and incongruent conditions, indicating racial bias, in the groups receiving active tDCS than in the group receiving a sham stimulation.

In another study, however, anodal tDCS effects on implicit alcohol associations were not pronounced in a group of hazardous drinkers (den Uyl, Gladwin, & Wiers, 2015). More precisely, den Uyl et al. (2015) tested two variants of the IAT, which contrasted alcoholic drinks versus nonalcoholic soft-drinks with either positive versus negative words (testing evaluations) or with approach versus avoidance words (testing motivation), before and after one out of three different stimulation conditions, targeting the left dlPFC, right IFG, or a sham condition. However, results did not corroborate changes in the alcohol IAT scores, but only showed a general reduction of response latencies in attribute trials (motivation or evaluative words) in the group receiving dlPFC stimulation (returned at contralateral supraorbital location).

In one earlier study, Gladwin, den Uyl, and Wiers (2012) even observed increased implicit associations from anodal tDCS, opposed to their predictions. Their study utilized the original insect–flower IAT, which yielded faster latencies for congruent combinations of insect pictures with negative words and flower pictures with positive words, relative to the crossed combinations. In their sham-controlled crossover experimental design, paradoxically, Gladwin et al. (2012) observed an enhanced implicit bias in the condition with anodal tDCS targeting the left dlPFC (returned at the right orbit), because response latencies were longer in the incongruent condition during active tDCS as compared to sham tDCS. The authors speculated that the PFC-activating anodal stimulation may actually have upregulated a dysfunctional network including implicit biases (Gladwin et al., 2012).

In fact, negative or unexpected stimulation results in cognitive performance may be linked to the claims that tDCS was generally ineffective (Horvath, Forte, & Carter, 2015) or at least that some configurations produce smaller effects than others in the cognitive domain (Jacobson, Koslowsky, & Lavidor, 2012). Alternatively, it may be possible that another tDCS configuration could be more effective, especially seeing the variety of possible protocols (e.g., Schroeder, Dresler, et al., 2017). Counterintuitively, but in line with above neuroimaging results, it may be even possible that left prefrontal networks were also involved in the activation of implicit

Table 1 Previous tDCS configurations for modulation of implicit associations

						
Target-Return Electrodes	F3 – SO	Fpz – Oz	Fpz – Oz	F3 – Xc	F3 – Xc	F3 – SO IFG[1] – SO
Polarity-Intensity	Anodal 1mA	Anodal 1mA	Cathodal 1mA	Anodal 1mA	Cathodal 1mA	Anodal 1mA (offline protocol)
Task	Insect-Flower Evaluation IAT	Ingroup-Outgroup Evaluation IAT	Ingroup-Outgroup Evaluation IAT	Space-Number SNARC	Space-Number SNARC	Alcohol-Soda Evaluation IAT & Motivation IAT
Result	▼ Increased Bias	▲ Reduced Bias	ø	ø	▲ Reduced Bias	▲ / ø Reduced overall RTs in attribute trials (F3-SO)
Authors	Gladwin, den Uyl, & Wiers, 2012	Sellaro et al., 2015	Sellaro et al., 2015	Schroeder et al., 2016, 2017	Schroeder et al., 2016, 2017	den Uyl, Gladwin, & Wiers, 2015

Note. In the first row, red and blue rectangles refer to anode and cathode placements on head and shoulder positions in the respective studies. Xc = extracephalic location

[1] IFG = electrode positioning refers to location on the crossing of F3, Cz, Fz, and T3

associations. Functionally, it was postulated that the activation of prefrontal networks may play a counterintuitive role in activating automatic associations (Gladwin et al., 2012; Schroeder & Plewnia, 2016). Accordingly, the inhibition of prefrontal activity should then also reduce the IAT effect.

With cathodal tDCS, firing probabilities are reduced due to hyperpolarization and increased resting membrane thresholds (Nitsche et al., 2003; Nitsche & Paulus, 2000). In working memory tasks, 1 mA cathodal tDCS of the left dlPFC reduced behavioral performance (Wolkenstein, Zeiller, Kanske, & Plewnia, 2014; Zaehle, Sandmann, Thorne, Jäncke, & Herrmann, 2011). From the previous IAT studies, it remained possible that a reduction of prefrontal activity may actually prove beneficial, as it was already shown for creative tool use (Chrysikou et al., 2013) and other behaviors (Schroeder & Plewnia, 2016). Actually, in previous studies on numerical cognition, we demonstrated that implicit spatial–numerical associations can be reduced specifically by 1 mA cathodal tDCS (Schroeder, Nuerk, & Plewnia, 2017; Schroeder, Pfister, Kunde, Nuerk, & Plewnia, 2016). However, although implicit spatial-numerical associations can be documented also in IAT double-classification tasks (Fischer & Shaki, 2016), implicit spatial–numerical biases are typically probed using much simpler stimulus–response compatibility paradigms in two-alternatives forced-choice classifications (e.g., judging whether a number is smaller or greater than "5," or another reference number) by means of a left-hand or right-hand key press. In such tasks, left-hand (right-hand) responses are faster for small (large) numbers, and vice versa (Dehaene, Bossini, & Giraux, 1993; Wood, Willmes, Nuerk, & Fischer, 2008). Despite somewhat resembling theoretical concepts, however, the generalizability of cathodal tDCS effects to different assessment procedures and implicit association effects could not be granted without further empirical evidence. For example, although different implicit biases may invoke a general cognitive process, it should be noted that assessment procedures and concepts are entirely distinct. Moreover, the respective indirect measurements that elucidate implicit associations in latency measures include different task instructions and procedures not necessarily comparable. Nevertheless, theoretically, the polarity correspondence principle predicts that both effects may share a common neurocognitive origin (Proctor & Cho, 2006; Proctor & Xiong, 2015), which could draw on the default characteristics of classification poles in learning and verbal processing (Nuerk, Iversen, & Willmes, 2004; Schroeder, Nuerk, et al., 2017). Following this theoretical consideration, PFC stimulation with cathodal tDCS could be hypothesized to elicit similar behavioral effects also in the IAT testing paradigm, providing an empirical test of this argument.

In the current study, in contrast to the two-alternatives forced-choice classification paradigms used to study implicit spatial–numerical associations, we utilized the prominent assessment procedure in the Implicit Association Test (IAT), a standardized response time (RT) paradigm and influential research tool in social, clinical, and cognitive psychology (De Houwer, Crombez, Koster, & De Beul, 2004; Gawronski & De Houwer, 2014; Roefs et al., 2011). In the IAT, participants categorize pictures of insects and flowers together with negative and positive words. Target classifications (insects vs. flowers) and attribute classifications (negative vs. positive words) are assigned to only two shared response keys, but target and attribute stimuli are presented intermixed in the two critical test blocks. The assumption is that RTs are faster in the congruent block than in the incongruent block, because targets and attributes are associated implicitly, share a common feature such as salience or familiarity, or because they allow for recoding (e.g., both insects and negatives are simply classified as negative; De Houwer, Geldof, & De Bruycker, 2005; Greenwald et al., 1998; Meissner & Rothermund, 2013; Mierke & Klauer, 2001; Rothermund & Wentura, 2004). Regardless of these potential mechanisms, the relative association strength (IAT effect) is inferred from performance (RT) differences in these two test blocks.

Given the standardized double-classification procedure fixed in the Implicit Association Test, the paradigm allows for large-ranging tests of associations, which can be realized by replacing target and attribute categories, and this was particularly informative in clinical and social psychology. In contrast to this, in numerical cognition, the assessment of implicit spatial–numerical associations includes a much simpler choice reaction task following only a simple rule, which detects associations based on the relative latency advantage or spatial information distributed to the right-hand or left-hand by a number-symbol assessment. Thus, although both constructs share certain similarities, because associations are implicitly activated without direct reflection or intention, it is not granted that cathodal tDCS effects would transfer to the different testing procedure in the IAT. Because our previous studies tested implicit spatial associations of numbers and documented efficacy of 1 mA cathodal tDCS to the left prefrontal cortex (Schroeder, Nuerk, et al., 2017; Schroeder et al., 2016), our hypothesis was that cathodal tDCS to the left prefrontal cortex would also reduce nonspatial implicit associations in the IAT effect. Theoretically, we expected a reduction of associations particularly due to the general polarity correspondence principle (Proctor & Cho, 2006), which explicitly predicts a shared cognitive process underlying both IAT effects and spatial–numerical associations in its most recent proposal (Proctor & Xiong, 2015, Table 1). Furthermore, the polarity correspondence principle lines up with the notion of verbal markedness and/or salience asymmetries in respective stimulus associations of the two effects (Nuerk et al., 2004; Rothermund & Wentura, 2004). However, besides the observation of implicit spatial–numerical associations also in an IAT paradigm by Fischer and Shaki (2016), these linkages were of theoretical nature. Moreover, although implicit associations are presumably apparent in both implicit biases, their neurocognitive underpinnings draw on entirely different fields of social psychology and mathematical cognition. Assessment of cathodal tDCS effects also in the IAT paradigm was a first step to corroborate this theoretical notion empirically, but to also lay foundation for more wide-ranging use cases of the cathodal stimulation rationale. Thus, the current study was a direct test of the generalizability of this theoretical stimulation effect.

Method

Participants

The study followed a sham-controlled crossover design, and participants were tested in two tDCS configurations (sham vs. active cathodal tDCS) on separate days (more than 2 days apart). A priori power analysis determined a required sample size of $N = 23$ participants to replicate the previously obtained stimulation effect on implicit spatial–numerical associations in a crossover design (effect size $f = 0.639$; Experiment 1 of Schroeder et al., 2016) with a power of $1 - \beta = 0.8$ and error rate of $\alpha = 0.05$. To counterbalance the orders of stimulation and IAT blocks across the sample, $N = 24$ healthy volunteers were recruited (mean age = 24.3 years, $SD = 4.7$ years, range: 19–37 years; three male; see Supplementary Analysis 1 for exploratory inspection of gender differences). All participants were right-handed (Oldfield, 1971) and native German speakers. Participants confirmed that they did not take any medication with CNS-acting drugs, had no previous or current neurological or psychiatric impairments, and two of them were low-frequency smokers (fewer than three cigarettes/day; remaining participants were nonsmokers). All participants provided written informed consent, and the study was approved by the Ethical Commission of the Medical Faculty University Tuebingen (local ID of approval: 030/2017BO2).

Cathodal transcranial Direct Current Stimulation (tDCS)

Direct current was generated by a CE-certified device (NeuroConn, Illmenau, Germany). An intensity of 1 mA was administered for 25 minutes, including a 5-minute pretask idle time during which participants were told to relax. During the first minutes of stimulation, adverse sensations are most pronounced, thus the sham stimulation was realized by administering the same stimulation for a duration of 40 s and then fading out subsequently. The 5-min idle time was adhered in both sham and cathodal tDCS sessions. As a consequence, the IAT procedure was started and completed either entirely during stimulation (active cathodal tDCS configuration) or entirely without active stimulation (sham tDCS configuration). Direct current was initiated and terminated with a linear 5-s ramp.

The target cathode rubber electrode (5 × 7 cm) was diagonally centered over F3 (left PFC; the position was ensured by tape measurements according to the international 10–20 system of electrode placement). The return anode rubber electrode (5 × 7 cm) was fixed over the right upper arm. This extracephalic return electrode placement avoids concurrent modulation of another brain region and thus delivers targeted modulation dependent on target cathode polarity (Schroeder et al., 2016; Wolkenstein et al., 2014). Both electrodes were buttered with a low-resistance EEG paste and additionally fixed with a bathing cap (target electrode) or adhesive tape (return electrode). Impedances were controlled to be below 10 kΩ prior to starting the sham or active stimulation.

IAT procedure

Participants performed the insect–flower evaluative IAT (Greenwald et al., 1998; Greenwald et al., 2009). The traditional double-classification procedure consists of a sequence of seven blocks (see Table 2) that subsequently introduced the bimanual classifications of 10 negative versus positive German words (from Rothermund & Wentura, 2004) and of 10 insect versus flower pictures (Hussey, 2017) in two practice blocks (1 and 2, respectively). Participants were asked to classify words as positive or negative (Block 1) and pictures as depicting insects or flowers (Block 2) by pressing one out of two keyboard keys with their left hand ("E") or right hand ("I") index fingers, corresponding to the positions of respective word and picture labels that were shown in the display. In the following combined test blocks (3 and 4), attribute words and target pictures appeared in randomized order. The response positions of negative/positive target labels adjacent to the insect/flower attribute labels on the left side/right side of the screen were determined by chance, such that these two test blocks were congruent for some participants (e.g., *insects* + *negative* and *flowers* + *positive* stimuli were classified by the same left and right key presses). For the other participants, these first test blocks (3 and 4) were presented in the incongruent response label constellation (e.g., *flowers* + *negative* and *insects* + *positive*). The positions of target labels were then reversed in the next practice block (5) and test blocks (6 and 7), such that performance during both congruent and incongruent block types was collected from all participants.

Participants were tested individually and seated at a comfortable distance (~60 cm from the experimentation computer). The experiment was implemented in PsychoPy (Peirce, 2007) based on a previous Open Source software of the IAT in Belgian language (Hussey, 2017). Classification labels (German words "Negativ", "Positiv", "Insekten", and "Blumen") were presented continuously on the respective sides in the top field of the computer screen. The background color was black. Attribute labels and stimulus words were written in light-green, whereas target labels were written in

Table 2 Trial numbers for each block type in the current experiment

	Block type	Stimuli assigned to left-hand key	Stimuli assigned to right-hand key	Number of trials
1	Attribute practice	Negative	Positive	20
2	Target practice	Insect	Flower	20
3	Test (congruent block)	Insect + Negative	Flower + Positive	40
4	Test (congruent block)	Insect + Negative	Flower + Positive	80
5	Target reversed practice	Flower	Insect	40
6	Test (incongruent block)	Flower + Negative	Insect + Positive	40
7	Test (incongruent block)	Flower + Negative	Insect + Positive	80

Note. The order of IAT-compatible (*insect* + *negative* vs. *flower* + *positive*) and IAT-incompatible mappings (*flower* + *negative* vs. *insect* + *positive*) in Test Blocks 3 and 4 and Blocks 6 and 7, respectively, was counterbalanced across participants in the current study. Half of participants completed the blocks in the displayed order; the other half completed the target practice and combined test blocks in the reversed order (i.e., starting with the target reversed practice in Block 2). As was argued in Greenwald et al. (1998; see also Nosek, Banaji, & Greenwald, 2002), the initial confrontation of IAT-incompatible double classifications can reduce the IAT effect (possible also due to involvement of cognitive control processes), and this was statistically confirmed in our data by larger IAT scores for the group of participants that received the compatible condition first (D-IAT = 0.63, *SE* = 0.07) as compared to the group that received the incompatible condition first (D-IAT = 0.31, *SE* = 0.7), $F(1, 22) = 12.31$, $p = .002$, $\eta_p^2 = .36$. However, entering this additional factor to the ANOVA on the stimulation effect did not produce a significant two-way interaction, $F(1, 22) = 0.20$, $p = .62$, suggesting that the order of presentation did not modulate the stimulation effect in the present results.

white, to maximize discrimination as separate categories (Nosek, Greenwald, & Banaji, 2007). In each trial, the classification stimulus (picture or word) appeared in the center of the screen until a response was given with the left hand ("E" key) or right-hand index finger ("I" key) on a standard QWERTZ keyboard, corresponding to the left-side and right-side label positions. After the correct response was given, a blank intertrial interval was shown for 400 ms, and then the next trial was started. Wrong responses had to be corrected by another key press.

The current task variant closely followed the recommendations outlined in Nosek et al. (2007), with the following adjustments. The order of compatible versus incompatible critical blocks was counterbalanced across participants in our design. Due to human error, the counterbalancing list assigned two fewer participants starting with compatible blocks to the sham stimulation in the first block. When these participants were removed in a separate analysis such that the combination was fully balanced, the reported stimulation results were stable. To improve reliability of the task, and to collect more data in each of the conditions, the number of trials was doubled in both congruent and incongruent blocks. Table 2 provides a summary of the resulting numbers of repetitions in each block. As was argued before, this manipulation could lead to generally somewhat diminished IAT effects (Greenwald, Nosek, & Banaji, 2003), rendering our current procedure relatively conservative.

Statistical analyses

Mean correct response times (RTs) and error rates were submitted without further transformation as dependent variables to separate ANOVAs comprising the repeated-measures factors IAT (congruent vs. incongruent block) × Trial Type (target vs. attribute trials) × Stimulation (cathodal vs. sham tDCS). The hypothesized outcome (stimulation effect) was the two-way interaction between IAT block and stimulation condition. Follow-up *t* tests were performed to outline changes between cathodal tDCS and sham tDCS (paired *t* test) in IAT effects (i.e., the RT difference between congruent and incongruent blocks) and to test the significance of IAT effects during both sessions individually (one-sample *t* test against zero).

Finally, we also computed the standardized D-IAT scores for the two stimulation conditions following the algorithm proposed by Greenwald et al. (2003) and tested the reduction of D-IAT by cathodal tDCS directly. The D-IAT composite index of the IAT effect is basically a standardized difference measure of performance in the incongruent vs. congruent test blocks of the tasks, divided by the pooled standard deviation. Moreover, the algorithm specifies outlier correction and extreme-value treatments [i.e., exclusion criteria for participants based on fast RTs (n = 0 were excluded), exclusion of long trials (>10 s), penalty for wrong responses (use of correction RT), no transformation of the resulting block mean RTs]. The formula for computing the D-IAT score was:

$$\text{D}-\text{IAT} = \text{M}\left(\frac{\text{RT}_{\text{B6}}-\text{RT}_{\text{B3}}}{\text{SD}_{\text{B6,B3}}}, \frac{\text{RT}_{\text{B7}}-\text{RT}_{\text{B4}}}{\text{SD}_{\text{B7,B4}}}\right)$$

For participants who performed blocks in reversed order (i.e., starting with the incongruent blocks in B3 and B4), the respective positions of B6 and B3, and B7 and B4, were switched in above formula (such that a positive D-IAT score would always reflect associations between *insect* + *negative* and *flower* + *positive* categories).

Results

RTs

Mean RTs for all block types, trial types, and stimulation conditions are shown in Fig. 1 and Table 3. Classification decisions were faster in the congruent IAT blocks (667 ms) than in the incongruent IAT blocks (793 ms), giving rise to a significant main effect of IAT in ANOVA, $F(1, 23) = 63.51$, $p < .001$, $\eta_p^2 = .73$. Target trials (containing insect vs. flower pictures; 663 ms) were faster answered to than attribute trials (negative vs. positive words; 798 ms) in the main effect of trial type, $F(1, 23) = 128.84$, $p < .001$, $\eta_p^2 = .85$. The main effect of stimulation was not significant, $F(1, 23) < 1$, $p = .435$.

Most importantly, there was a significant two-way Stimulation × IAT interaction, $F(1, 23) = 7.68$, $p = .011$, $\eta_p^2 = .25$. The RT difference between congruent and incongruent trials (IAT effect) was significantly reduced during cathodal tDCS as compared to sham tDCS, $t(23) = 2.77$, $p = .011$, $d = 0.61$. Nevertheless, IAT effects significantly differed from zero during both sham tDCS (153 ms), $t(23) = 8.57$, $p < .001$, as well as during cathodal tDCS (98 ms), $t(23) = 5.04$, $p < .001$. Further individual inspection of IAT block types could not statistically confirm the isolated events of RT decrease in incongruent trials (−42 ms), $t(23) = 1.68$, $p = .106$, and RT increase in congruent trials (+14 ms), $t(23) = 1.00$, $p = .330$, which suggested only a modest tDCS effect on bias in general, as also indicated by the effect size of the IAT effect reduction (see also Fig. 1). The stimulation effect was not further qualified by a three-way interaction with trial type, $F(1, 23) = 2.39$, $p = .136$.

Accuracy

Mean error rates are reported in Table 4. More accurate responses were given in the congruent IAT blocks (94.0%) than in the incongruent IAT blocks (92.7%), but the main effect of IAT in ANOVA was much less substantial than in RTs and was not statistically significant, $F(1, 23) = 2.98$, $p = .098$, $\eta_p^2 = .12$. Performance appeared to be more accurate in target trials (94.3%) than in attribute trials (92.4%), but the respective main effect of trial type was not statistically significant either, $F(1, 23) = 3.69$, $p = .067$, $\eta_p^2 = .14$. There was no main effect of stimulation, $F(1, 23) < 1$, $p = .922$, and no significant two-way Stimulation × IAT interaction, $F(1, 23) < 1$, $p = .727$, nor were there further significant interaction terms, $F\text{s} < 1.71$, $p\text{s} > .205$.

D-IAT score

Finally, we also computed the composite D-IAT scores for the two sham and cathodal tDCS sessions by applying the improved scoring algorithm (Greenwald et al., 2003). In brief, the D-IAT score is a standardized RT difference measure (considering both test blocks and pooled RT standard deviations; see Method section).

There was a significant difference between the sham session and cathodal tDCS session in the hypothesized direction, $t(23) = 1.95$, $p_{\text{one-tailed}} = .032$, $d = 0.39$ (see Fig. 2). Complementary to the previous observation in RTs, implicit associations were more pronounced in the sham session (D-IAT = 0.53, $SE = 0.05$) than in the session concurrent to cathodal tDCS (D-IAT = 0.42, $SE = 0.07$; the D-IAT score technically ranges between −2 and 2).

Adverse sensations of tDCS

Adverse sensations were assessed by a questionnaire after both sham and active tDCS sessions, consisting of 7 items on a 5-point Likert scale (Brunoni et al., 2011). Participants reported more intense tingling after active cathodal tDCS ($M = 2.79$, $SE = 0.23$) than after sham tDCS ($M = 2.29$, $SE = 0.16$), $t(23) = 2.22$, $p = .037$, $d = 0.45$. The remaining comparisons were not significant and all values are reported in Supplementary Table S1.

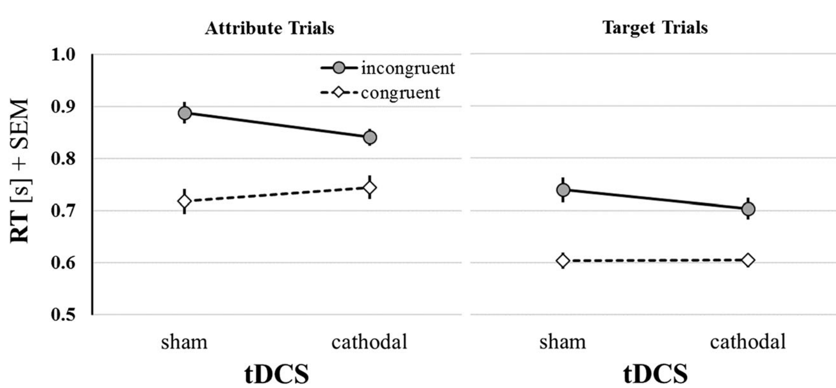


Fig. 1 Mean response times during sham tDCS and active cathodal tDCS as a function of IAT block type (incongruent vs. congruent). Left and right columns show data separately for attribute trials (positive vs. negative words) and relatively faster target trials (insect vs. flower pictures). Error bars reflect standard errors of the mean

Table 3 Mean RTs and IAT effects during sham and cathodal tDCS

	IAT congruent		IAT incongruent		IAT effect
	Mean RTs [ms]	*SD*	Mean RT [ms]	*SD*	dRT [ms]
Sham tDCS					
Attribute trials	718	81	888	147	170
Target trials	603	93	739	130	136
Cathodal tDCS					
Attribute trials	744	105	841	112	97
Target trials	605	76	703	103	98

Blinding

Participants were asked immediately after sham and active cathodal tDCS whether they had received a sham stimulation (with comparable sensations, but without modulations of cognitive processing). Fifteen of 24 participants correctly guessed the tDCS session and 15/24 (partially different) participants correctly guessed the sham session. Data were submitted to a chi-square test, $\chi^2(1) = 3.00$, $p = .083$. Although participants tended to guess correctly, results did not corroborate a significant link between guesses and sham stimulation, thus blinding was successful. We also explicitly asked whether the stimulation had improved their task performance on a 1–5 Likert scale (ranging from *not at all* to *tremendously*), but there was no explicit perception of any behavioral changes neither after anodal tDCS ($M = 1.22$, $SD = 0.42$) nor after sham tDCS ($M = 1.17$, SD = 0.39; $p = .747$).

Discussion

We tested the general capability of 1 mA inhibitory, cathodal tDCS to reduce performance measures of implicit associations the insect–flower IAT. As expected by the literature, participants were consistently faster when flowers and positive words (insects and negative words) were evaluated by the same response (congruent block), as compared to the condition that paired flowers and negative words (insects and positive words) to the same response (incongruent block; IAT effect). Stimulation of the left PFC by cathodal tDCS was utilized to hyperpolarize resting membrane potentials and thus reduce cortical activity in this area. Unlike previous attempts with anodal tDCS, we delivered this type of inhibitory stimulation to directly reduce the activation of implicit associations. Thus, the assumption was that cathodal tDCS would effectively target an automatic system involved in activation of implicit associations, as opposed to possible effects of anodal tDCS on cognitive control regulation. As anticipated, a significant reduction of IAT effects was observed specifically in response times, and the stimulation effect was also reflected in the standardized D-IAT scores.

The current results are complementary to the previous tDCS studies that explored the effectivity of activity-enhancing anodal tDCS on cognitive control processes and IAT regulation (den Uyl et al., 2015; Gladwin et al., 2012; Sellaro et al., 2015). In contrast to these previous studies, we here explored whether it was possible to reduce implicit associations directly with the cathodal, inhibitory tDCS polarity

Table 4 Mean error rates and IAT effects during sham and cathodal tDCS

	IAT congruent		IAT incongruent		IAT effect
	% Error	*SD*	% Error	*SD*	dError
Sham tDCS					
Attribute trials	7.1	7.7	7.4	7.2	0.3
Target trials	5.1	5.5	7.1	5.1	2.0
Cathodal tDCS					
Attribute trials	7.4	6.5	8.4	6.8	1.0
Target trials	4.3	5.0	6.2	4.8	1.9

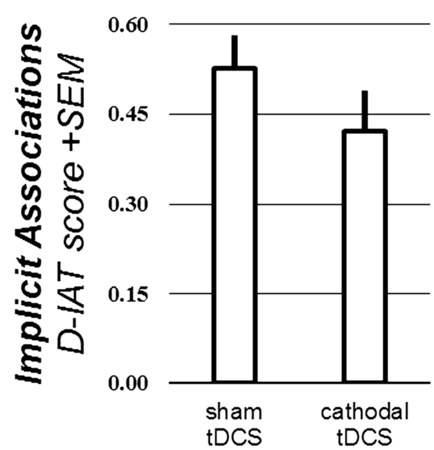


Fig. 2 Mean D-IAT effect during sham tDCS and cathodal tDCS. Composite scores (D-IAT) were obtained from applying the improved scoring algorithm by Greenwald et al. (2003). Error bars reflect standard errors of the mean

over the left PFC. Specifically, we predicted that 1 mA activity-reducing cathodal tDCS would reduce the IAT effect, as observed before with spatial–numerical associations in different paradigms (Schroeder, Nuerk, et al., 2017; Schroeder et al., 2016). Although it may be surprising at first that the PFC would causally contribute to the seemingly automatic and unintended activation of implicit associations, actually, resembling stimulation effects were also expected by the polarity correspondence principle (Proctor & Cho, 2006; Proctor & Xiong, 2015). Thus, the analogous stimulation effects in entirely different assessment procedures and implicit constructs may actually suggest a common neurocognitive process susceptible to cathodal tDCS. In general, the results corroborate the potential of beneficial cathodal stimulation effects due to a reduction in task-irrelevant cognition that would require PFC activation.

Importantly, the observed results are not only consistent with the proposed stimulation rationale but also with previous empirical findings. For instance, Gladwin et al. (2012) reported on a pattern of results effectively orthogonal to our findings, and their study showed an enhancement of IAT effects by anodal tDCS of the same PFC target region in the insect–flower IAT. In the study by Sellaro et al. (2015), a cathodal tDCS configuration over medial PFC actually also induced a descriptive (yet nonsignificant) reduction of the racial bias. Since both tDCS configuration had relatively little spatial focality, a spillover to more medial or lateral sites could not be excluded.

Theoretically, the present results also provide an important conceptual test of the observed effects of tDCS on spatial–numerical associations, which were attributed to depend on linguistic structures (such as small–large and before–after classification polarities in simple two-alternative forced-choice classifications). However, it was not clear whether stimulation effects would generalize to nonspatial associations and other testing procedures such as provided by the IAT. Nevertheless, the effectivity of left-hemispheric cathodal tDCS in both domains is again consistent with the notion of verbal processing, as opposed to right-hemispheric polarization in other studies (e.g., Ruf, Fallgatter, & Plewnia, 2017).

Potential relevance for cognitive and clinical tDCS trainings

The capability to reduce implicit associations with cathodal tDCS may be interesting for several applications. For instance, combined trainings of implicit approach tendencies with tDCS have been explored in the treatment of addiction (e.g., using the alcohol approach–avoidance task; den Uyl et al., 2017), but implicit associations may be involved in other clinically relevant behaviors as well (De Houwer, 2002). Nevertheless, the results reported here should be seen only as a first starting point for theoretically motivated modification paradigms with cathodal tDCS, considering that several limitations exist: (i) It is not yet established that the observed modulations are longer lasting. Training studies achieved sustainability of 3–9 months after a combined tDCS cognitive training over three sessions (Ruf et al., 2017), but the current result was drawn from single-session observations. (ii) Furthermore, it is not clear whether the observed modulations of IAT effects also translate into relevant explicit behavior, as already the transition between IAT measurements and explicit self-reports is often rather low (but incremental; Fiedler et al., 2006; Greenwald et al., 2009). Moreover, indirect measurements during different stimulation sessions cannot differentiate between relief from implicit associations per se, or the mere impact thereof on performance. Possibly, a combined training might allow for reliable changes in IAT effects, which could also have effects on spontaneous behavior in situations that are dominated by reflexive behavior (e.g., binge eating), but this potential mechanism must be tested in respective studies first. (iii) Although theory and combined evidence from different previous tasks indicate a certain generalizability (Schroeder, Nuerk, et al., 2017; Schroeder et al., 2016), it could be possible to obtain bolder or weaker modulations in different stimuli. This might be explained by additional codes that do not draw on implied mechanisms (e.g., salience) as much, or by more complex self-related behaviors. For example, Rothermund and Wentura (2004) acknowledged that some IAT effects may include emotional or self-relevant processing that could not be explained exhaustively by salience processing. In our previous elaboration of verbal markedness in spatial–numerical associations (Schroeder, Nuerk, et al., 2017), we explicitly emphasize the necessity of multiple cognitive codes and the possibility of switching between them using tDCS. Moreover, posterior-parietal cathodal tDCS (with supraorbital return) was not equally effective to modulate both implicit spatial–numerical associations and parity–space markedness associations, but showed selectivity in another study (Di Rosa et al., 2017). (iv) The current study design did not include an active control condition, which limits inferences on the specificity of our stimulation configuration (but see Table 1 for other protocols in previous studies). (v) Interestingly, in alcohol-addicted patients, a puzzling IAT effect pertains to the negative and avoidant evaluation of alcohol, which is not accounted for by salience asymmetries but by alcohol use (Houben & Wiers, 2006). Thus, especially in patient populations that may have developed different cognitive processes to certain stimuli (e.g., compensation strategies), it must be established whether linguistic markedness, symmetry, or individually refined salience confines to any observed effect.

Finally, it should be recognized that implicit associations per se are not necessarily dysfunctional in all cases. Instead, implicit activations can also allow for low-cost and functional decision-making akin to heuristics (Gigerenzer & Gaissmaier, 2011), thus enabling rapid and adaptive action. For example, a negative association triggered by a spider or a wasp may guard an agent's health in the first place by inducing avoidant behavior. On the contrary, implicit approach associations could worsen pathological addictive behaviors. Independent of the physiological effect of stimulation, a reduction of implicit associations by cathodal tDCS may help or hurt dependent on the exact task setting. It will be mandatory to further investigate the personal and general processes that lead to potentially harmful implicit associations (e.g., approach biases in obese participants; Kemps & Tiggemann, 2015) in order to fully account for potential bias modifications with tDCS in the future.

Summary

In conclusion, the current study demonstrates the capability to reduce implicit associations in the IAT effect by means of cathodal tDCS to the left prefrontal cortex. Thus, we consistently complement a series of previous results. The present findings are in line with the modulation of spatial–numerical associations in single categorization tasks (Schroeder, Nuerk, et al., 2017; Schroeder et al., 2016), with the effects of anodal tDCS on IAT biases (den Uyl et al., 2015; Gladwin et al., 2012; Sellaro et al., 2015), and with the proposed stimulation rationale of activity-decreasing cathodal tDCS. Intriguingly, reduced activity seemed beneficial even in this simple categorization task, possibly by reduction of dysfunctional network activity (Schroeder & Plewnia, 2016). Although some interesting perspectives emerge for therapeutic applications, there is little evidence for long-term modulations of implicit associations, the link to external behaviors is unclear, and generalizability to clinical populations or to other socially sensitive IAT effects is likely to be examined in future clinical studies.

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