

# Applications of transcranial Direct Current Stimulation (tDCS) for modulating the Face Inversion Effect (FIE): Reducing and Enhancing Recognition

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## Abstract

We report a large study examining the effects of tDCS on the FIE. Subjects randomly assigned to one of the four tDCS groups and engaged with an old/new recognition task involving upright and inverted faces. 1) Sham tDCS during the study phase and recognition task; 2) Anodal tDCS during the study phase followed by sham tDCS during the recognition task; 3) Anodal tDCS during the study phase followed by cathodal tDCS during the recognition task; 4) Cathodal tDCS during the study phase followed by sham tDCS during the recognition task. Group 2 confirmed that anodal tDCS reduces the FIE vs. sham (Group 1) by disrupting performance for upright faces. Group 3 showed that cathodal tDCS applied after anodal, increased the FIE vs. Group 2, bringing it back to sham level, by enhancing upright faces. Group 4 revealed that cathodal tDCS applied after sham has no effect on the baseline FIE.

**Keywords:** Face Inversion Effect; Face Recognition; Perceptual learning; tDCS

## Introduction

The face inversion effect (FIE) is the phenomenon where recognition performance is impaired when we are presented with upside-down faces, as opposed to when the same faces are presented upright (Yin, 1969). Initially, this pronounced effect served as an indicator of the face-specific nature of recognition processes, evidenced by a greater inversion effect for faces than for other stimuli such as houses or cars (Yin, 1969; Valentine, 1988; Maurer et al., 2002 for a review). This view was later contested when Diamond and Carey (1986) demonstrated a similar inversion effect with dog images among dog breeders, indicating that expertise, rather than face specificity, might drive this effect.

In 1997, two main studies bolstered the perceptual expertise hypothesis. Gauthier and Tarr (1997) found that familiarization with artificial stimuli called Greebles enhanced recognition performance in their upright orientation but not when inverted. Participants were better at identifying parts within a familiar Greeble's configuration when shown upright, even though the inversion effect wasn't directly measured. This study highlighted how pre-exposure to novel stimuli in an upright orientation improved performance. Similarly, McLaren (1997) showed that pre-exposure to prototype-

defined categories of non-orientated artificial stimuli (checkerboards) led to an inversion effect via a matching task. Building on McLaren's work, Civile, Zhao, et al. (2014) used the same checkerboard stimuli in an old/new recognition task, commonly used in face recognition research, to examine the inversion effect. Results indicated a robust inversion effect for checkerboards associated with familiar categories versus novel ones (see also McLaren and Civile, 2011). These findings were framed using the MKM model (McLaren et al., 1989; McLaren and Mackintosh, 2000; McLaren et al., 2012), which suggests that the modulation of salience through error contributes to perceptual learning underpinning the inversion effect for both checkerboards and faces.

To delve deeper into the mechanisms underlying the inversion effect and explore how to modulate them, Civile, Verbruggen et al. (2016) adapted a transcranial Direct Current Stimulation (tDCS) procedure, originally utilized in learning and categorization research (Ambrus et al., 2011), to their checkerboard inversion effect paradigm. Ambrus et al. employed a bilateral bipolar-non-balanced montage, positioning the anode over the target stimulation area (Fp3), which fMRI studies have identified as highly active in categorization tasks (Seger et al., 2000), and the cathode/return over the opposite supraorbital area (Fp2) during a categorization learning task. Their results demonstrated that active anodal tDCS could diminish the prototype distortion effect. McLaren et al. (2016) expanded these findings with the same tDCS setup applied to categorization learning using the prototype-defined checkerboards from Civile, Zhao et al. (2014). In the study by Civile, Verbruggen et al. (2016), this method applied to the checkerboard inversion effect showed that anodal tDCS reduced the inversion effect compared to sham/control tDCS, due to disrupted recognition of upright familiar checkerboards. The procedure was then extended to the FIE, revealing that anodal tDCS reduced FIE compared to sham/control tDCS and an active control group using a different tDCS target area, by impairing recognition performance for upright faces (Civile, Obhi et al., 2017; Civile, McLaren et al., 2018; Civile, Obhi et al., 2019; Civile, Cooke et al., 2020). These findings suggest shared underlying

mechanisms in the inversion effects for both checkerboards and faces, providing evidence that perceptual learning plays a main role in FIE.

According to the MKM model of perceptual learning (McLaren et al., 1989; McLaren and Mackintosh, 2000; McLaren et al., 2012), when observers are pre-exposed to category exemplars, they tend to focus on features shared between the exemplars and the category prototype. These common features become strongly linked to the category, which reduces their salience due to a lower prediction error. In contrast, unique and unpredictable features of each exemplar retain their salience because they aren't subject to the same reduction. This modulation of feature salience is crucial for perceptual learning, allowing observers to concentrate on unique features and recognize exemplars from the same category when presented upright, which is the orientation learned during pre-exposure. Upon inversion, this mechanism falters because the new, unfamiliar spatial arrangement of features makes them less predictable, disrupting the usual salience balance between common and unique features in upright stimuli. Anodal tDCS further disrupts this salience modulation, enhancing generalization over discriminability. As a result, common features become more prominent due to mutual activation, while unique features lose salience because they lack additional activation. This shift in perceptual learning reduces the ability to differentiate between upright faces, causing them to appear more similar and thus diminishing the inversion effect. This explanation is further corroborated by simulation work using a Matlab-based MKM model that simulates the impact of tDCS on the inversion effect (Civile, McLaren et al., 2023).

It is vital to highlight the critical manipulations made to the specific tDCS montage and behavioral paradigms aimed at enhancing our understanding of how anodal tDCS over the Fp3 region modulates the FIE. For example, Civile, McLaren et al. (2018, Experiment 3) conducted an active control study where the tDCS montage targeted a different scalp area, the right Inferior Frontal Gyrus (rIFG), to determine if this stimulation would evoke the same effects on the FIE as observed with anodal tDCS at the Fp3 site. The rIFG was chosen because prior research indicated that tDCS applied over this area was effective in various tasks, such as go/no-go tasks (Cunillera et al., 2014, 2016; Stramaccia et al., 2015). However, no studies had previously examined the influence of tDCS at the rIFG on perceptual learning tasks. The results demonstrated a robust FIE in both sham and anodal groups, with no significant differences between them. This finding suggests that targeting any other scalp region does not replicate the tDCS effects observed at Fp3. Similarly, Civile, McLaren et al. (2021) investigated whether anodal stimulation over the PO8 site—identified as relevant based on ERP findings related to the N170 component (Civile, Waguri et al., 2024; Civile, Waguri et al., 2020; Civile, Elchlepp, et al., 2018; Civile, Elchlepp et al., 2012a,b; Rossion et al., 2002; Busey & Vanderkolk, 2005)—would impact face

recognition, as indexed by the composite face effect. The PO8 site had previously been employed by Yang et al. (2014) and Renzi et al. (2015) to evaluate tDCS effects on the composite face effect. Although Yang et al. found some evidence of tDCS modulation, Renzi et al. did not replicate these findings and observed no significant effects of tDCS. In their study, Civile, McLaren et al. (2021) found that anodal tDCS at both PO8 and Fp3 did not affect the composite face effect. However, anodal tDCS at Fp3 led to a reliable decrease in overall recognition performance, which was anticipated since the task involved all upright faces. More recently, Civile, McCourt et al. (2025) tested the effects of anodal tDCS at Fp3 with the return channel positioned at Cz (as an active control) compared to the return channel at Fp2 (the established procedure). The results indicated that anodal tDCS at Fp3 did not influence the inversion effect for either checkerboards or faces when the return channel was at Cz. Collectively, the findings from these active control studies underscore the importance of the specific tDCS montage (anodal tDCS at Fp3 with return channel at Fp2) in achieving the desired effects on the FIE.

In subsequent research, the tDCS procedure was adapted for a matching task designed to ensure comparable performance levels between face and checkerboard stimuli (Civile, Quaglia et al., 2021). The findings confirmed that anodal tDCS at Fp3, with the return channel at Fp2, led to a reduced inversion effect for both faces and checkerboards compared to sham/control tDCS. For both types of stimuli, this reduction in the inversion effect during the anodal condition was primarily attributed to impaired recognition performance for upright stimuli. Additionally, Civile, McLaren et al. (2020) examined how the timing of anodal tDCS delivery—during the study phase versus the recognition phase of an old/new recognition task—affected the FIE. The results were significant, indicating that in both conditions, the FIE was considerably impaired due to disrupted recognition performance for upright faces in comparison to the sham condition. This supports the immediate effects of anodal tDCS on the FIE. Overall, the findings from studies targeting the Fp3 site demonstrate that anodal stimulation significantly diminishes the FIE by reducing recognition performance for upright faces, with no observable effects on inverted faces.

In recent research, Civile, McCourt et al. (2024) explored, for the first time, the effects of reversed polarity tDCS (cathodal stimulation) on the FIE at the Fp3 site. Each participant underwent two tDCS sessions—one during the study phase and another during the recognition phase of an old/new recognition task—totalling 20 minutes of stimulation. Participants were randomly assigned to one of three tDCS groups: 1) Sham tDCS during both phases (control group); 2) Anodal tDCS during the study phase followed by sham tDCS during recognition; and 3) Anodal tDCS during the study phase followed by cathodal tDCS during recognition. The results from the anodal-sham group confirmed a reduction in the FIE compared to the sham-sham group,

consistent with previous literature on the effects of anodal tDCS (e.g., Civile, McLaren et al., 2018). Notably, the reduction in the FIE observed in the anodal-sham group was significantly different from the robust FIE recorded in the anodal-cathodal group, which exhibited levels similar to the control group. This provides the first evidence in the literature indicating that cathodal stimulation following anodal stimulation can restore the FIE to a level comparable to the control group, suggesting that cathodal tDCS can effectively reverse the effects of anodal tDCS. Importantly, the restoration of the FIE by cathodal tDCS was attributed to enhanced recognition performance for upright faces, returning to control levels.

In the current study, we aim to replicate these novel findings and further investigate the effects of cathodal tDCS on the FIE. To this end, we conducted a larger tDCS study utilizing the same tDCS groups as in Civile, McCourt et al.'s (2024) research, alongside an additional group receiving cathodal tDCS during the study phase followed by sham tDCS during the recognition phase. This new group reflected the procedure of the anodal-sham group but centered on cathodal tDCS. The objective is to determine whether the effects of cathodal tDCS specifically reverse the impacts of anodal tDCS on the FIE or if they produce a general enhancement of performance for upright faces, even from baseline

## Method

### Subjects

A total of 160 participants (112 female, mean age = 20.5 years) took part in the study, all of whom were students at the University of Exeter. Participants participated for either monetary compensation or course credit. Subjects were randomly assigned to one of the four tDCS groups, with 40 individuals in each group. All methods were conducted following the relevant guidelines and regulations, as approved by the Psychology Research Ethics Committee at the University of Exeter. Informed consent was obtained from all participants. The sample size was determined based on the work of Civile, McCourt et al. (2024), which utilized the same old/new recognition task, included stimuli counterbalancing, followed the same tDCS procedure, and employed a double-blind between-subject design.

### Materials

The study utilized the same set of stimuli as Civile, McCourt et al. (2024), comprising 128 male and 128 female face images, which were standardized to grayscale and displayed on a black background. These images were sourced from the Psychological Image Collection at Stirling open database (pics.stir.ac.uk) and had also been employed in previous tDCS and FIE research (e.g., Civile, McLaren et al., 2018; Civile, Obhi et al., 2019; Civile, McLaren et al., 2020; Civile, McLaren et al. 2022). Each stimulus measured 5.63 cm x

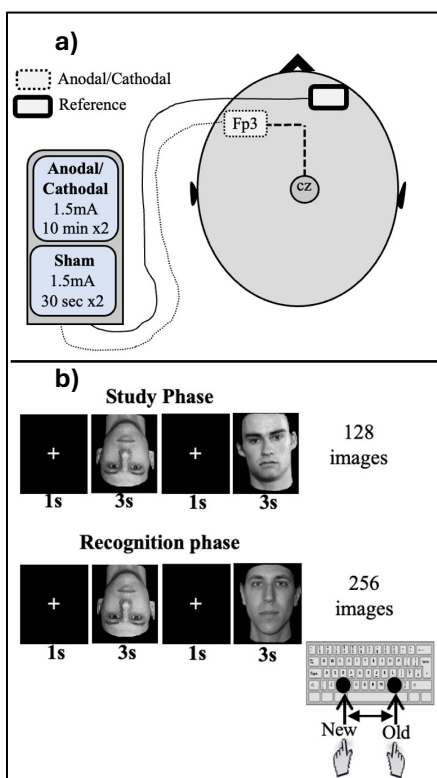
7.84 cm and was presented at a resolution of 1280 × 960 pixels. The experiment was conducted using SuperLab 4.0.7b on an iMac computer. Participants were seated approximately 70 cm away from the screen displaying the images.

### TDCS apparatus and montage

The tDCS setup and montage used in this study closely mirrored that of Civile, McCourt et al. (2024), with the addition of a new group receiving cathodal tDCS followed by sham tDCS. Stimulation was delivered using a battery-driven constant current stimulator (neuroConn DC-Stimulator Plus) equipped with a pair of surface sponge electrodes (7 cm x 5 cm, total area of 35 cm<sup>2</sup>) soaked in saline solution, applied to the scalp at the designated stimulation sites. A double-blind procedure was implemented, relying on the neuroConn study mode, in which the experimenter entered numerical codes (provided by a separate investigator not involved in running the experiment) to switch between 'active' (anodal or cathodal) and 'sham' stimulation. During the anodal and cathodal conditions, a direct current of 1.5 mA was delivered for 10 minutes (including a 5-second fade-in and 5-second fade-out) starting as the participants began the computer task. The same tDCS setup and stimulation parameters were employed in both conditions, with the positions of the two electrodes swapped. In the anodal condition, a bilateral bipolar-non-balanced montage was used, with one electrode (anode) placed over the target stimulation area (Fp3) and the other electrode (cathode/return) positioned on the opposite supraorbital area (Fp2) above the right eyebrow. This setup is consistent with previous studies (e.g., Civile, Verbruggen et al., 2016; Civile, McLaren et al., 2018; Civile, Obhi et al., 2019; Civile, McLaren et al., 2020; Civile, McLaren et al., 2023; Civile, McCourt et al., 2025). In the cathodal condition, the electrodes were reversed, placing the cathode at Fp3 and the anode at Fp2, serving as the return channel (Civile, McCourt et al., 2024). For the sham group (which included subjects receiving either anodal or cathodal tDCS setups), the same stimulation mode was displayed on the stimulator. Participants experienced the identical 5-second fade-in and 5-second fade-out, but with the stimulation intensity of 1.5 mA maintained for only 30 seconds. This was followed by small current pulses delivered every 550 ms (0.1 mA over 15 ms) for the remainder of the 10 minutes to check impedance levels (Figure 1a). Each participant completed two tDCS sessions (one during the study phase and one during the recognition phase), totaling 20 minutes of stimulation. Participants were randomly assigned to one of four tDCS groups: 1) Sham tDCS during both the study and recognition phases; 2) Anodal tDCS during the study phase followed by sham tDCS during recognition; 3) Anodal tDCS during the study phase followed by cathodal tDCS during recognition; and 4) Cathodal tDCS during the study phase followed by sham tDCS during recognition.

## The behavioural task

The behavioral paradigm was identical to that of Civile, McCourt et al. (2024) and consisted of an old/new recognition task, where the first tDCS stimulation occurred during the study phase and the second during the recognition phase. During the study phase, participants completed 128 trials. Each trial began with a 1-s fixation cue displayed in the center of the screen, followed by the presentation of a face image for 3-s. The faces were evenly divided between male and female, with both upright and inverted orientations presented in a randomized and intermixed order. No response was required from the participants during the study phase; instead, they were instructed to memorize as many faces as possible. The recognition phase included 256 trials, with 50% consisting of stimuli from the study phase and the remaining 50% featuring novel stimuli, also evenly split between upright and inverted orientations, presented one at a time in random order. Each trial commenced with a 1-s fixation cue in the center of the screen, followed by the face stimulus displayed for a maximum of 3-s. Participants responded using the “X” and “.” keys to indicate whether they believed a given stimulus had been previously shown (i.e., ‘old’) or was novel (i.e., ‘novel’) in the study phase. The designation of response keys was counterbalanced across participants. If no response was made within the 3-s, the subject timed out, and the next trial began automatically (Figure 1b).



**Figure 1.** Panel a illustrates the tDCS montage adopted in our study. Panel b represents a schematic illustration of the behavioural task used in our study.

## Results

In agreement with previous studies (Civile, McCourt et al., Civile, McLaren, et al., 2018; Civile, Obhi et al., 2019; Civile, McLaren, et al., 2020; Civile, McLaren et al., 2023; Civile, McCourt et al., 2025) our primary measure was accuracy in the recognition task. Accuracy for male and female faces was collapsed based on previous studies that found no differences between them. The data from all the subjects in each experimental condition was used to compute a  $d$ -prime ( $d'$ ) sensitivity measure for the recognition task where a  $d'$  of 0 indicates chance-level performance. We assessed performance against chance for upright and inverted faces in each tDCS group showing that for all conditions we found  $p < .001$  for this analysis. Each p-value reported for the comparisons between conditions is two-tailed, and we also report the F or t value along with effect size ( $\eta^2p$ ).

A 2x4 mixed model ANOVA was conducted to examine the within-subjects factor of *Orientation* (upright, inverted) and the between-subjects factor of *tDCS Condition* (sham-sham, anodal-sham, anodal-cathodal, cathodal-sham). This analysis revealed a significant main effect of *Orientation*,  $F(1, 156) = 145.35$ ,  $p < .001$ ,  $\eta^2p = .48$ , indicating a robust FIE. There was a significant main effect of *tDCS Condition*,  $F(1, 156) = 3.03$ ,  $p = .031$ ,  $\eta^2p = .05$ . This effect was driven largely by differences in performance for upright faces across tDCS groups. There was also a trend toward a significant interaction between *Orientation* and *tDCS Condition*,  $F(1, 156) = 2.63$ ,  $p = .052$ ,  $\eta^2p = .05$ .

Subsequent independent t-tests compared the size of the inversion effects (upright – inverted) across each tDCS group. These tests confirmed significant differences in the FIE between the sham-sham and anodal-sham groups,  $t(78) = 2.51$ ,  $p = .014$ ,  $\eta^2p = .07$ , affirming that anodal tDCS reliably reduces the FIE. Importantly, there was also a significant difference in the FIE between the anodal-sham and anodal-cathodal groups,  $t(78) = 2.11$ ,  $p = .037$ ,  $\eta^2p = .05$ , supporting Civile, McCourt et al (2024)’s conclusion that cathodal tDCS can reverse the FIE reduction induced by anodal tDCS. No significant difference in the FIE was observed between the sham-sham and anodal-cathodal groups,  $t(78) = .30$ ,  $p = .77$ ,  $\eta^2p < .01$ , further evidence of cathodal tDCS’s ability to restore FIE to baseline. Lastly, the absence of a significant FIE difference between the sham-sham and cathodal-sham groups,  $t(78) = .65$ ,  $p = .51$ ,  $\eta^2p < .01$ , indicates that cathodal tDCS from baseline does not affect the FIE.

Performance for upright faces alone was compared across tDCS groups. In the anodal-sham group, performance for upright faces ( $M = .40$ ,  $SE = .07$ ) was significantly reduced compared to the sham-sham group ( $M = .62$ ,  $SE = .05$ ),  $t(78) = 2.28$ ,  $p = .025$ ,  $\eta^2p = .06$ , the anodal-cathodal group ( $M = .70$ ,  $SE = .06$ ),  $t(78) = 2.99$ ,  $p = .003$ ,  $\eta^2p = .10$ , and the cathodal-sham group ( $M = .63$ ,  $SE = .06$ ),  $t(78) = 2.22$ ,  $p = .028$ ,  $\eta^2p = .06$ . No differences were found between the sham-sham group and both the anodal-cathodal group,  $t(78) = .89$ ,  $p = .37$ ,

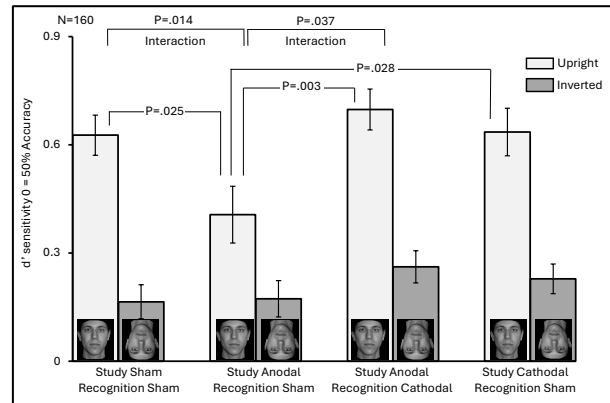
$\eta^2p = .01$ , and the cathodal-sham group,  $t(78) = .10$ ,  $p = .092$ ,  $\eta^2p < .01$ .

Analysis of inverted face recognition revealed no significant difference between the anodal-sham group ( $M = .17$ ,  $SE = .05$ ) and the sham-sham group ( $M = .16$ ,  $SE = .05$ ),  $t(78) = .125$ ,  $p = .90$ ,  $\eta^2p < .01$ . Similarly, no significant differences were detected between the anodal-sham and anodal-cathodal groups,  $t(78) = 1.31$ ,  $p = .19$ ,  $\eta^2p = .02$ , or between the anodal-sham and cathodal-sham groups,  $t(78) = .85$ ,  $p = .40$ ,  $\eta^2p < .01$ . Additionally, no significant differences were found between the sham-sham group and both the anodal-cathodal group,  $t(78) = 1.49$ ,  $p = .14$ ,  $\eta^2p = .02$ , and the cathodal-sham group,  $t(78) = 1.02$ ,  $p = .31$ ,  $\eta^2p = .01$  (Figure 2).

For completeness paired sample t-tests were conducted on the FIE for each tDCS group. The sham-sham group displayed the expected large FIE ( $M(\text{difference}) = .46$ ,  $SD = .37$ ),  $t(39) = 7.87$ ,  $p < .001$ ,  $\eta^2p = .61$ . In the anodal-sham group a reduced but still significant FIE was found ( $M(\text{difference}) = .23$ ,  $SD = .44$ )  $t(39) = 3.33$ ,  $p = .001$ ,  $\eta^2p = .22$ . In the anodal-cathodal group there was an FIE of similar size to that in the sham-sham group ( $M(\text{difference}) = .43$ ,  $SD = .41$ ),  $t(39) = 6.64$ ,  $p < .001$ ,  $\eta^2p = .53$ , as well as in the cathodal-sham group ( $M(\text{difference}) = .41$ ,  $SD = .38$ ),  $t(39) = 6.73$ ,  $p < .001$ ,  $\eta^2p = .54$ .

### Bayes Factor Analysis

According to the procedure devised by Dienes (2011) we conducted a Bayes analysis on the difference between the FIE in anodal-sham and anodal-cathodal. We used as the *priors* the differences found in Civile, McCourt et al (2024)'s study, setting the standard deviation of  $p$  (population value | theory) to the mean for the difference between the FIE in anodal-sham group vs that in the anodal-cathodal group (0.28). We used the standard error (0.07) and mean difference (0.20) between the FIE in the anodal-sham group vs. that in the anodal-cathodal group in our current study. This gave a Bayes factor of 22.57, which is very strong evidence (greater than 10, for the conventional cut-offs see Jeffrey, 1961; Dienes 2011) that these results are in line with Civile, McCourt et al (2024) with cathodal tDCS to increase the FIE compared to anodal tDCS. We then conducted a Bayes analysis on the difference between upright faces in anodal-sham and anodal-cathodal. We used as the *priors* the differences found in Civile, McCourt et al (2024), setting the standard deviation of  $p$  (population value | theory) to the mean for the difference between the upright faces in anodal-sham group vs that in the anodal-cathodal group (0.25) in Civile, McCourt et al (2024). We used the standard error (0.07) and mean difference (0.29) between the upright faces in the anodal-sham group vs. that in the anodal-cathodal group in our current study. This gave a Bayes factor of 1537, which is again very strong evidence that these results are in line with Civile, McCourt et al (2024), supporting the effects of cathodal tDCS enhancing performance for upright faces after that anodal tDCS has been applied.



**Figure 2** reports the results from our study. The x-axis shows the stimulus conditions across the three tDCS groups, the y-axis shows  $d'$ . Error bars represent s.e.m. Performance for upright and inverted faces in all tDCS groups was significantly above chance (for all conditions we found  $p < .001$  for this analysis).

### Discussion

The study reported herein aimed to validate the effects observed in the anodal-cathodal group from Civile, McCourt et al. (2024) and to investigate the impact of cathodal tDCS applied independently from baseline. Consistent with the previous findings, the results for the anodal-cathodal indicated that the FIE could be reversed to baseline levels, comparable to those in the sham-sham group, following the application of cathodal tDCS. Bayesian analysis provided additional support for cathodal tDCS's ability to counteract the effects induced by anodal tDCS on the FIE. This modulation was primarily due to the restoration of performance for upright faces to normal levels after cathodal tDCS.

A novel finding from our study was the performance of the cathodal-sham group, which exhibited no significant effects on the FIE. Unlike the anodal-cathodal group, the application of cathodal tDCS from baseline did not alter the FIE or the recognition performance for upright faces alone. This suggests that the primary function of cathodal tDCS is to reverse the effects of anodal tDCS on the FIE, rather than to provide a general enhancement in face recognition performance. These results reinforce the specificity of cathodal tDCS as a mechanism for restoring perceptual performance disrupted by prior anodal stimulation, rather than serving as a tool for enhancing baseline recognition of faces. This insight is critical in understanding the effects of anodal and cathodal tDCS on the FIE. The lack of effects on the FIE or performance for recognizing upright faces in the cathodal-sham group indicates that the positive effects noted in the anodal-cathodal group cannot be attributed to a general enhancement in recognition. Instead, cathodal tDCS appears particularly effective in counteracting the effects of preceding anodal tDCS, supporting the proposed link to perceptual learning mechanisms. Reflecting on the foundational study by Civile, Verbruggen et al. (2016), which examined the effects of anodal tDCS at Fp3 on the checkerboard

inversion effect, their results compared baseline cathodal tDCS with anodal tDCS. While they did not incorporate a control group in the same experiment, they noted that anodal tDCS reduced the checkerboard inversion effect compared to cathodal tDCS, which exhibited an effect size similar to the sham group from a separate study. Our current findings, now including a sham-sham group, clarify these earlier implications: cathodal tDCS does not impact the inversion effect or recognition performance when applied from baseline, but it effectively reverses the impacts of anodal tDCS on perceptual learning. This specificity underscores the role of cathodal tDCS in restoring disrupted perceptual processes rather than broadly enhancing them.

Future research should aim to extend the investigation by applying cathodal tDCS exclusively during the recognition task, following the application of sham tDCS during the study phase. This important manipulation has yet to be explored and could help address the key theoretical question surrounding the current results. Despite robust evidence supporting a perceptual learning-based explanation for the observed effects, there remains a possibility that cathodal tDCS in the anodal-cathodal group may be contributing to enhanced retrieval rather than reversing perceptual learning. It is conceivable that anodal tDCS partially affects the encoding of facial information during the study phase, while cathodal tDCS may enhance the retrieval of the remaining encoded information that was not modulated by the anodal tDCS. Therefore, a study in which cathodal tDCS is delivered during the recognition phase, following sham tDCS during the study phase, could potentially yield improved recognition performance for upright faces compared to the sham condition (i.e., an increased FIE). This would suggest that cathodal tDCS enhances retrieval from baseline-encoded faces following sham stimulation. Conversely, if cathodal tDCS shows no significant effects, and the FIE remains at baseline levels, this would lend further support to the perceptual learning account. Such results would indicate that the feature salience modulation mechanism underlying perceptual learning is not enhanced from baseline by cathodal tDCS. Overall, these future investigations will be crucial for clarifying the role of cathodal tDCS in both encoding and retrieval processes as well as perceptual learning within the context of face recognition and the FIE.

Overall, our work advances the tDCS and perceptual learning literature by demonstrating that cathodal stimulation can effectively reverse the effects of anodal stimulation on the FIE. Importantly, this provides us with a tDCS paradigm capable of, within the lab and within-subjects, initially reducing face recognition abilities—effectively inducing temporary face-blindness—and subsequently restoring those abilities within a total of 20 minutes of tDCS stimulation (10 minutes each for anodal and cathodal stimulation). Thus, we can utilize tDCS to first diminish and then enhance the FIE and recognition performance for upright faces.

More broadly, our findings contribute to ongoing research examining the effects of tDCS on perceptual learning. While these studies differ in their specific procedures, they provide valuable context. For instance, Pisoni et al. (2015) found that anodal tDCS at the T3 scalp area significantly reduced performance in a face-name association learning task compared to sham. In another study, Peters et al. (2013) applied anodal tDCS to the Oz scalp area during a two-day Gabor patch orientation detection task. Their results indicated performance improvements for those who received cathodal or sham tDCS on the first day, but no improvements for those receiving anodal tDCS, suggesting that anodal tDCS impaired overnight consolidation of perceptual learning. Barbieri et al. (2016) showed that anodal tDCS at PO8, with the cathode at Fp1, improved face and object recognition performance, although the inversion effect was not tested.

Moreover, our results enhance the body of knowledge on tDCS and face recognition. For example, Yang et al. (2014) investigated anodal tDCS at P8 on face recognition, noting a reduced composite face effect size but lacking specific statistical analysis regarding performance changes. In contrast, Renzi et al. (2015) found no modulation of the composite face effect with anodal tDCS at the OFA area, aligning with findings by Civile, McLaren et al. (2021). However, Renzi and colleagues observed a blocking effect on learning Mooney faces (black and white distorted faces), indicating impaired face detection learning. Additional analysis by Costantino et al. (2017) revealed that cathodal tDCS at PO8 could induce effects similar to the own-race bias, as evidenced by reduced recognition performance of Western Caucasian faces by non-Western Caucasian participants. More recently, Civile and McLaren (2022) provided the first evidence that anodal tDCS at Fp3 could reduce the own-race bias, indexed by the FIE, eliminating the disparity between recognizing own-race and other-race faces among Western Caucasians.

Collectively, these results suggest that tDCS can modulate perceptual learning and face recognition, offering a deeper understanding of the neurocognitive mechanisms underpinning these essential skills.

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