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RESEARCH REPORT

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Transcranial direct current stimulation over the left anterior temporal lobe during memory retrieval differentially affects true and false recognition in the DRM task

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Abstract

Transcranial direct current stimulation (tDCS) is a form of non-invasive brain stimulation that has been used to modulate human brain activity and cognition. One area which has not yet been extensively explored using tDCS is the generation of false memories. In this study, we combined the Deese-Roediger-McDermott (DRM) task with stimulation of the left anterior temporal lobe (ATL) during retrieval. This area has been shown to be involved in semantic processing in general and retrieval of false memories in the DRM paradigm in particular. During stimulation, 0.7 mA were applied via a 9 cm² electrode over the left ATL, with the 35 cm² return electrode placed over the left deltoid. We contrasted the effects of cathodal, anodal, and sham stimulation, which were applied in the recognition phase of the experiment on a sample of 78 volunteers. Results showed impaired recognition of true memories after both anodal and cathodal stimulation in comparison to sham stimulation, suggesting a reduced signal-to-noise ratio. In addition, the results revealed enhanced false recognition of concept lure items during cathodal stimulation compared to anodal stimulation, indicating a polarity-dependent impact of tDCS on false memories in the DRM task. The pathway by which tDCS modulated false recognition remains unclear: stimulation may have changed the activation of irrelevant lures or affected the weighting and monitoring of lure activations. Nevertheless, these results are a first step towards using brain stimulation to decrease false memories. Practical implications of the findings for real-life settings, for example, in the courtroom, need to be addressed in future work.

KEYWORDS

anterior temporal lobe, brain stimulation, DRM, false memories, tDCS

Abbreviations: ATL, anterior temporal lobe; cm, centimetre; CSC, controlled semantic cognition (framework); d', d-prime; DRM, Deese-Roediger-McDermott; EVSD, equal variance signal detection; GABA, gamma-aminobutyric acid; HTSD, high-threshold signal detection; mA, milliampere; MANOVA, multivariate analysis of variance; min, minutes; ms, milliseconds; mV, millivolt; NMDA, N-methyl-D-aspartate (receptor); ROC, receiver operating characteristic; tDCS, transcranial direct current stimulation; TMS, transcranial magnetic stimulation; UVSD, unequal variance signal detection.

1 | INTRODUCTION

Correctly remembering past events is crucial for everyday life and a false memory can have significant impacts on a person's life as well as that of others. For example, in a criminal trial, a witness falsely remembering an event can have severe negative implications for the trial and the verdict. One way to experimentally induce very basic memory illusions comes in the form of the Deese-Roediger-McDermott (DRM) task (Deese, 1959; Roediger & McDermott, 1995).[1] In short, the DRM task requires participants to remember several word lists, whereby each list has a target word associated with it which is not presented during learning. During the retrieval phase this target word, called the concept lure item, is falsely remembered by participants. In the present study, we show that recognition of both learned list words and concept lures can be modulated by transcranial electrical stimulation.

1.1 | Modelling false memories in the DRM task

The DRM task typically involves participants learning word lists which are associated with a specific conceptual lure (e.g., the list might contain medicine, hospital, nurse and physician but not the word doctor which serves as the conceptual lure). The typical procedure has participants learn several lists in an encoding phase and after a distractor task, participants have to retrieve the originally learned words. This retrieval phase ordinarily involves participants making a recognition judgement for the learned old words as well as for the critical new concept lures and other new words not presented during initial encoding. The typical finding is that false recognition of critical lures approaches the hit rate of originally learned items and that false recognition responses are made with high confidence (Roediger & McDermott, 1995). The DRM illusion can be viewed within an activation-monitoring framework (for a recent review see Gallo, 2010). The framework describes the interaction of top-down (e.g., adding associations based on the presented information) and bottom-up (e.g., feeling of familiarity) influences on the illusion. The added association combined with a misattribution of familiarity leads to a failure to correctly identify the source for concept lures in the DRM paradigm. Thus, false or illusory memories are a by-product of a constructive memory process that underlies both true and false memory retrieval.

DRM task performance in recognition testing can be examined using a signal-detection approach (Huff & Bodner, 2013; Huff et al., 2015). The approach assumes that recognition strength is a continuum and that studied items (i.e., items presented in the learning phase) are more likely to be remembered than new items or the concept lures. Following this logic, hits and false alarms can be computed for each item type, and used to compute d' which provides an index of memory sensitivity or discriminability (Wickens, 2010; Yonelinas & Parks, 2007). Crucially, d' can be calculated for conceptual lures and old list items separately, meaning that both correct as well as false memory recollection processes can be differentiated. Further, any modification of performance due to an outside influence such as non-invasive brain stimulation can be precisely traced back to the item type and process it modulated. Past research has shown that concept orientation is positively correlated with increased false recognition of concept lures, but has no impact on the recognition of old list items (Brainerd & Reyna, 2007; Holliday & Weekes, 2006) and patients with dementia who are known to be more literal and less concept-driven show less susceptibility to false memories (Simons et al., 2005; Snyder et al., 2004).

1.2 | Neurophysiological underpinnings of the DRM task and false memory

The DRM illusion relies on the spread of (brain) activation between representations of semantically associated items to concept lures during encoding and the failure to reject the concept lure as "old" due to a source monitoring malfunction at retrieval (Gallo, 2010). Evidence points towards the left anterior temporal lobe (ATL) as a crucial area involved in human semantic memory functioning, especially if this memory is relevant to the person (Binder et al., 2009; Wong & Gallate, 2012). Specifically, during the recognition phase in the DRM paradigm, the neural overlap between the representation of studied items and lures as well as the activation within the left ATL has been shown to predict the degree of false memory retrieval (Chadwick et al., 2016). Additional evidence exists that the individual GABA-level in the left ATL is positively correlated to better performance in semantic association tasks, suggesting that the ATL exerts inhibitory control over irrelevant semantic associations (Jung et al., 2017), a finding that may generalize to the DRM and other false memory paradigms (Abe, 2012).

With regard to the study of false memories in the DRM paradigm, the ATL has not yet been extensively investigated using brain stimulation techniques. Non-invasive brain stimulation (NIBS) can generate causal evidence for the direct involvement of a brain area in a cognitive process, although network-wide effects of NIBS are possible such that a modulation of one area has knock-on effects on other, connected regions. For example, one study used repetitive transcranial

[1]It should be noted that different misinformation paradigms partially rely on different mechanisms and consequently different forms of illusory memory do not necessarily correlate (Bernstein et al., 2018; Ost et al., 2013).

magnetic stimulation (TMS) to target the left ATL after the encoding phase but before the retrieval phase in the DRM task; results showed an average 36% reduction in false memories in the TMS condition compared to sham stimulation (Gallate et al., 2009). The authors argued that the perturbation of left ATL functioning reduced false memories due to decreased strength of semantic activation. This fits with other accounts that suggest performance improvements in the DRM task after the loss of left ATL functioning (Miller et al., 1998; Mummery et al., 2000; Treffert, 2009; Young et al., 2004). The ATL is a key component in the controlled semantic cognition framework (CSC; Ralph et al., 2016). It is considered an amodal hub in the processing of semantic information, which represents the semantic similarity among concepts (Patterson et al., 2007). Loss or perturbation of ATL functioning can lead to severe mental impairment, including semantic dementia, because the central role of the ATL can hardly be compensated by other brain areas. Although in theory compensation within networks is possible if a node was perturbed, the frontal areas cannot alleviate problems arising in the left ATL, as they are reliant on the input from the information associated with and processed in the left ATL (Pobric et al., 2007).

Another method of non-invasive brain stimulation is transcranial direct current stimulation (tDCS). Compared with TMS, tDCS is easier to set up and considered similarly safe (Woods & Martin, 2016). Further, tDCS is capable of directly enhancing or diminishing activity within an area via the use of one or more electrodes applied to the scalp with a reference electrode either being mounted on the scalp or extracephalically. The applied current flows between electrodes and interacts with the underlying brain area, thereby inducing diminutions or enhancements of cortical excitability (Nitsche et al., 2008; Woods & Martin, 2016). Application of tDCS during task performance (termed online tDCS) includes sub-threshold modulations in the resting membrane potentials, which consequently can alter the spontaneous firing rate of neurons and modify their response to incoming signals. Specifically, during anodal tDCS an initial depolarization due to an Na^+ influx leads to the opening of voltage-gated Ca^{2+} channels of the NMDA receptor (Stagg et al., 2018; Stagg & Nitsche, 2011). Thus, during anodal tDCS action potentials can be triggered more easily. This increase in action potentials can lead to an increase or decrease in performance depending on which process is modified and also depending on the pre-activation of the area (Miniussi et al., 2013). Conversely, during cathodal tDCS, the neuron is hyperpolarized. The cell membrane is most permeable to K^+ ions, which are encouraged by the external negative pole to passively follow their concentration gradient and flow out of the cell to reach their equilibrium potential of −90 mV (Gazzaniga et al., 2014). This hyperpolarization closes voltage-dependent channels and prevents the NMDA receptor from being permeable to Ca^{2+} ions (Stagg & Nitsche, 2011). Evidence for these mechanisms comes from pharmaceutical studies showing that Ca^{2+} as well as Na^+ channel blockers eliminate anodal tDCS effects, while the same drugs have no effects of cathodal tDCS outcomes (Dayan & Cohen, 2011; Nitsche et al., 2003).

Thus, anodal online stimulation might enhance the signal and lead to a performance increase but it is also possible that the stimulation adds additional noise to the system and prevents effective processing in the area. Similarly, cathodal tDCS can change the signal-to-noise ratio by altering the overall neuron firing threshold and reducing the amount of action potentials in the area. If too much noise is present in the system this might lead to a performance enhancement, whereas if the process is largely signal-dependent, cathodal tDCS decreases performance. Specifically, with regard to the DRM paradigm anodal (cathodal) stimulation might improve (impair) correct recognition of learned items. However, it is also possible that any stimulation may disrupt the fine-tuned recognition system and regardless of stimulation polarity, the correct recognition may be negatively affected. Further, tDCS might impact illusory memories (i.e., the false recognition of lure items) in a polarity-dependent way by up- and down-regulating areas involved in the recognition process.

Converging evidence for a polarity-specific tDCS effect comes from research in multiple cognitive domains ranging from interference control (e.g., Friehs et al., 2019; Frings et al., 2018; Loftus et al., 2015) and response inhibition (e.g., Friehs & Frings, 2018, 2019b; Stramaccia et al., 2015) to working memory (e.g., Friehs & Frings, 2019b, 2020; Mashal & Metzuyanim-Gorelick, 2019). However, even though several studies have already investigated tDCS effects on episodic memory (e.g., Stramaccia et al., 2017; Zwissler et al., 2014), a recent meta-analysis suggests that tDCS effects on episodic memory are inconsistent at best, and more research is needed to understand the circumstances under which tDCS modulates episodic memory (Galli et al., 2019). False memories, and specifically the DRM task, have so far not been the target of many tDCS studies. For example, Boggio et al., (2009) applied tDCS over the left temporal cortex during encoding and reported significantly reduced false memories. Further, Pergolizzi and Chua (2015) applied tDCS over the parietal lobe during the recognition test and reported higher false recognition rates (i.e., worse performance) (Pergolizzi & Chua, 2015). Taken together, although these studies provide initial evidence that performance and false memories in the DRM paradigm can be manipulated using tDCS, the aforementioned research did not target the left ATL during retrieval.

More recently, Meléndez et al. (2021) reported an increase in correct recognition and decrease in false recognition of phonologically related lures following anodal stimulation over the left ATL throughout the entirety of a list learning task. Díez et al (2017a) reported similar results using a DRM task, observing a reduction in false recognition following anodal (but not cathodal) stimulation during the study phase of the task. The timing of the stimulation in these studies raises questions regarding the mechanism of effect, as tDCS may have interfered with either encoding or retrieval. To further investigate this issue, Díez et al (2017b) applied tDCS during the recognition phase and found no effects of either anodal or cathodal stimulation. The authors inferred from this that effects of anodal stimulation reported by Díez et al. (2017a) must derive from modulation of the encoding process. In both of these studies, however, stimulation condition was assessed between subjects and as a result the analyses may be underpowered. We are therefore wary of drawing conclusions from the null results reported by Díez et al. (2017b). Here we employ a within-subjects design which provides greater power to address this question.

1.3 | Present study

The present study investigates the relation between the neural activity in the left ATL and the DRM illusion. Through the use of tDCS over the ATL during the recognition process in the DRM task, a direct causal link between the underlying neural activation and the performance can be established. The ATL plays a key role in the conceptualization and is considered a semantic hub in the human brain (Jung et al., 2017; Pobric et al., 2010; Ralph et al., 2016; Wong & Gallate, 2012). Importantly, activation within this area during recognition has been directly correlated with the DRM illusion (Chadwick et al., 2016). Consequently, we hypothesize that tDCS over the left ATL impacts the DRM illusion. We aimed to compare anodal, cathodal, and sham stimulation. The guiding hypothesis was a polarity- and process-specific modulation of memory performance. First, based on recent neuroimaging evidence, we expected that anodal and cathodal stimulation would impact lure recollection in a polarity-dependent way. While anodal tDCS should reduce false recollection, cathodal tDCS should increase false memories. Within the context of the activation-monitoring framework, we hypothesize that due to the role of the ATL in exerting inhibitory control over irrelevant semantic links, anodal tDCS over the ATL decreases the activation of lures by increasing the inhibition of irrelevant semantic links (Abe, 2012; Gallo, 2010; Pobric et al., 2007). Conversely, cathodal tDCS might decrease the inhibition efficacy and therefore increase the number of false lure recognitions. Second, based on previous studies and simulations that show a signal-to-noise ratio modulation due to tDCS, we expected that both anodal and cathodal tDCS impact the recollection of old list words (Miniussi et al., 2013).

2 | MATERIALS AND METHODS

2.1 | Sample

Eighty healthy students from the University of Trier (56 female, 24 male) with a mean age of 23.69 ($SD = 3.61$) were recruited for the study, two subjects needed to be excluded due to technical reasons. G*Power (v3.1.9.4) sensitivity analysis for goodness-of-fit testing with one degree of freedom indicated a required medium effect size of $w = 0.313$ or $\eta^2 = 0.048$ when alpha was set to 0.05 and power to 0.80 (Faul et al., 2007). All participants were native German speakers, had normal or corrected to normal vision and no prior neurological, psychiatric or cardiovascular disease. They were compensated either by course credit or a payment of 10 Euro. Written informed consent was obtained from all participants. The study protocol was in accordance with the guidelines of the Declaration of Helsinki and approved by the local ethics committee.

2.2 | Experimental design and procedure

Participants were randomly assigned to one of three tDCS conditions: (1) anodal, (2) cathodal or (3) sham online stimulation of the left ATL. Participants were not told which condition they were assigned to. Upon entering the laboratory, each participant underwent a standardized procedure. First, a questionnaire concerning exclusion criteria and demographic data had to be filled out. Second, the participant was prepared for the stimulation and the tDCS electrodes were mounted. Third, participants completed the learning phase of the DRM paradigm (see below). Fourth, participants were asked to complete a difficult Sudoku problem as a fifteen-minute distraction task. Fifth, tDCS was applied during the test phase of the DRM paradigm. Sixth, participants filled out a tDCS side-effect questionnaire and had their hair washed after the study.

2.3 | DRM task

The DRM task procedure was modelled after Chadwick et al., (2016). The original word lists were translated and adapted for the German language (Bäuml & Kuhbandner, 2003; Chadwick et al., 2016; Stadler et al., 1999; all materials publicly available on PsychArchives). In detail, the DRM task consists of three phases: a learning phase, a distractor phase, and a test phase. During the learning phase, participants were presented with 40 four-word DRM lists. The words of each set were semantically related to a specific target word, that is, the concept lure, and were presented sequentially. Participants were instructed to memorize all presented words for an upcoming test. Each word was presented for 0.5 s with a 3 s interval

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between lists. The order of all 40 lists as well as the words within the lists were randomized for each subject. During the 15-min distractor phase, participants were asked to do a hard Sudoku puzzle. In the test phase, a recognition test on all 160 learned words, the 40 concept lures, and an additional 160 semantically unrelated, new words was administered. The order of items in the recognition test was pseudorandomized; for each participant, a new random item order was drawn such that no word and list sequence was repeated across participants. Each word was presented on the screen until response. Item recognition was tested by asking participants to rate their confidence of each word being old or new on a 1 to 6 scale ranging from "definitely old" to "definitely new." Participants were encouraged to use the whole range of the six-point rating scale to specify their degree of confidence. Items were presented in the middle of the screen, together with a rating scale schematically depicted in the lower part of the screen. Participants were asked to enter their responses on a PC keyboard. Confidence ratings were used to construct item-recognition receiver-operating characteristics (ROCs) that allow to examine stimulation on old items' and concept lures' memory strength independent of participants' response criteria (see below).

2.4 | Transcranial direct current stimulation

Direct current was applied by a four-channel constant current generator (DC-STIMULATOR by NeuroConn, Ilmenau, Germany). In all stimulation conditions a 9 cm² (3 × 3 cm) electrode was positioned over the left ATL (corresponding to BA 38 at the midpoint between F7, T7 and FT9 position according to the 10–20 EEG electrode system; Chatrian et al., 1988), while a 35 cm² (5 × 7 cm) reference electrode was placed on the left deltoid muscle. The localization procedure for the stimulation condition is similar to a previous TMS study targeting the ATL (Gallate et al., 2009); targeted the midpoint between T7 and FT7. For both the anodal and cathodal online tDCS condition, a current of 0.7 mA was applied for 19 min with an additional 30 s ramp-up/-down phase, thus totalling 20 min of stimulation. In the sham condition, the aforementioned ramp-up/ramp-down phase was included at the start and the end of the supposed stimulation period. The stimulation was controlled via a panel PC. Current flow patterns were simulated using the SimNIBS software (Thielscher et al., 2015). For details on the stimulation see Figure 1.

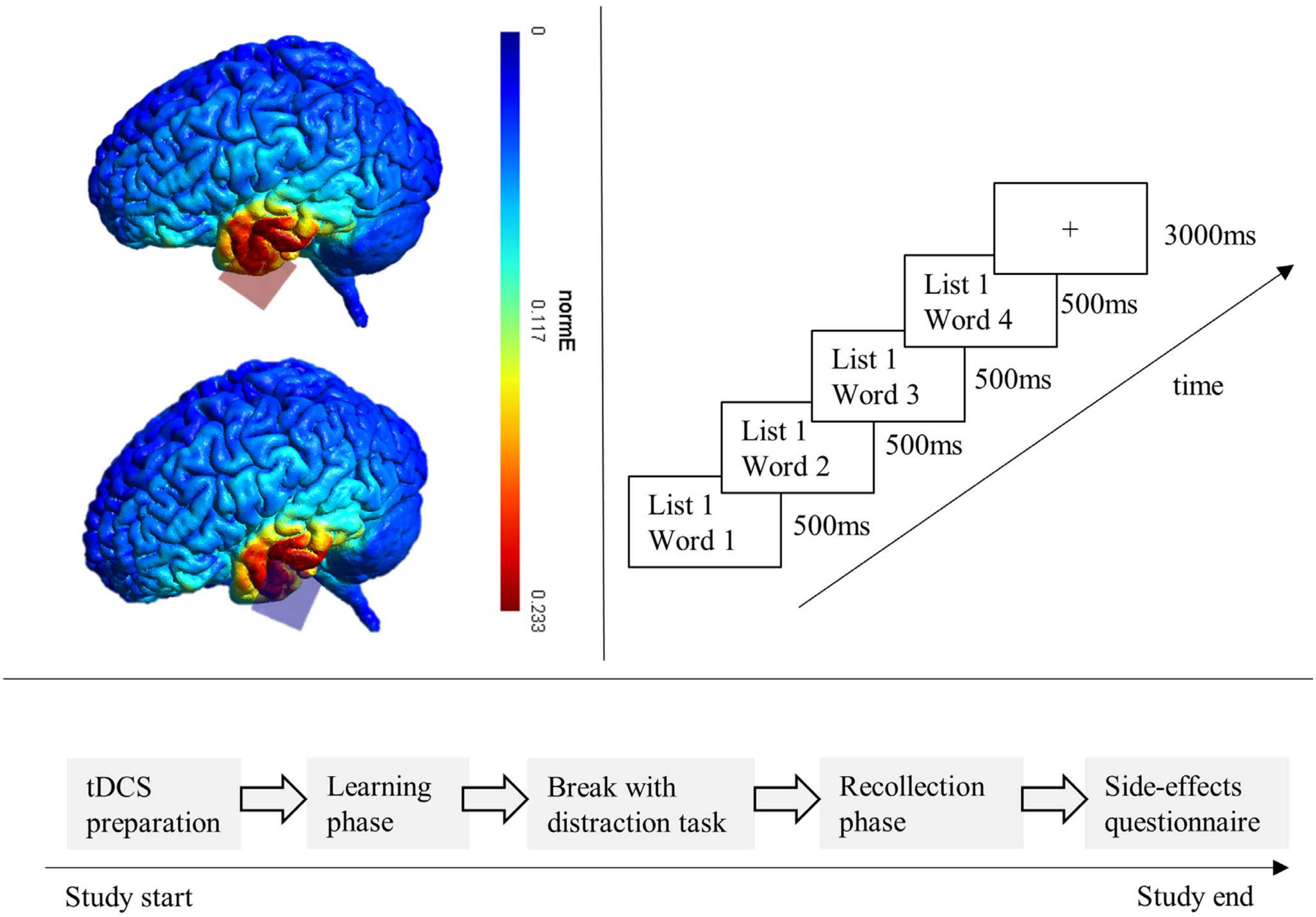

FIGURE 1 Figure depicts the study procedure (bottom), the DRM task flow (right) as well as the current flow simulations for the present tDCS montage (left)

2.5 | Data analysis

In an initial step, all participant data were manually screened for feasibility. It should be noted that, indicated by a negative score difference between hits and false alarms, three participants misunderstood the scale and provided inverted answers across all questions (i.e., an item that was definitely new was not rated as a 6 but rather as a 1). Their scores were inverted. Using signal-detection analysis, item-recognition data were examined on the basis of group data in ROC analysis (Pastötter et al., 2016; Wixted, 2007; Wixted & Mickes, 2010; Yonelinas & Parks, 2007). ROC curves were created by plotting accumulated hit rates for old items (old-new ROCs) and false alarms for concept lures (lure-new ROCs) against accumulated false alarm rates for new items across response criterion points associated with the different levels of the confidence-rating scale. Three different memory models were compared in terms of how well they were able to explain the data. The equal-variance signal detection (EVSD) model assumes that the old and new items have the same variability in memory strength (Banks, 1970), whereas the unequal-variance signal detection (UVSD) model assumes that old items have a larger variance in memory strength than new items, due to differences in encoding strength (Hilford et al., 2002). The high-threshold signal detection (HTSD) model assumes that recollection is an all-or-none high-threshold process, whereas familiarity is a continuous process that is governed by an equal-variance detection model (Yonelinas, 1994). Parameter estimation and goodness-of-fit statistics were calculated with maximum likelihood estimation and the Solver (TM) tool in Microsoft Excel (Dunn, 2010). When simultaneously considering all three stimulation conditions in goodness-of-fit testing, the EVSD has 18 free parameters (3 d's and 15 response-criterion values), the UVSD 21 parameters (3 d's, 3 standard deviations, and 15 response-criterion values), and the HTSD also 21 parameters (3 recollection, 3 familiarity, and 15 response-criterion values). The EVSD thus has 12, the UVSD 9, and the HTSD also 9 degrees of freedom to test each model's goodness of fit to the data. To anticipate, the UVSD model was best able to describe the data and, therefore, the memory strength parameter d' of the UVSD model was considered for further analysis.

Next, a two-step analysis was carried out to examine how the memory strength parameter d' of the UVSD model varied with experimental stimulation. This analysis was calculated separately for old-new and lure-new ROCs. In the first step of the analysis, we analysed whether d' varied between anodal and cathodal stimulation. In the second step, we examined the effects of anodal and cathodal stimulation in comparison to sham stimulation. If it turned out that there was no significant difference in d' between anodal and cathodal stimulation conditions in the first analysis step (as we expected for the old-new ROCs based on the signal-to-noise hypothesis), we examined whether d' in the sham condition was different from mean d' in the anodal and cathodal stimulation conditions (in fact, based on the signal-to-noise hypothesis, we expected that d' in the sham condition was larger than mean d' in the anodal and cathodal stimulation conditions). Alternatively, if it turned out that there was a significant difference in d' between anodal and cathodal stimulation conditions in the first analysis step (as we expected for lure-new ROCs based on the different-polarity hypothesis), we examined whether d' in the sham condition differed from d' in the anodal stimulation condition and d' in the cathodal simulation condition, respectively (in fact, based on the different-polarity hypothesis, we expected that d' in the sham condition was larger than d' in the anodal stimulation condition but smaller than d' in the cathodal simulation condition). Statistical testing was done using the Solver™ tool in Microsoft Excel (Dunn, 2010) and JASP (JASP Team 2020).

3 | RESULTS

3.1 | True memories

3.1.1 | Old-new ROCs

Goodness-of-fit testing showed that the UVSD model was best able to explain the data (see Table 1), even though no model fits the data perfectly as indicated by the significant χ^2-tests for all three models. Figure 2 shows the ROC curves as suggested by the UVSD model. In the two-step analysis, we examined whether the memory strength parameter d' of the UVSD model varied with stimulation. In the first step, we compared cathodal and anodal stimulation and found no difference in d' between conditions, $\chi^2(1) = 2.48$, $p = 0.118$. In the second analysis step, we found that d' in the sham condition was significantly larger than mean d' in the anodal and cathodal stimulation conditions, $\chi^2(1) = 16.64$, $p < 0.001$, $\eta^2 = 0.21$. Together, these results suggest impaired correct recognition of old items due to cathodal or anodal tDCS to the left ATL as compared to sham stimulation.

3.1.2 | False memories: lure-new ROCs

Again, goodness-of-fit testing indicated that the UVSD model was best able to explain the data (see Table 1); in fact, the fit of the UVSD model for the false-memory data was satisfactory as indicated by the non-significant goodness-of-fit test, $\chi^2(9) = 13.78$, $p = 0.130$. Figure 2 shows the ROC curves as suggested by the UVSD model. In the two-step analysis, comparison of the cathodal and anodal stimulation conditions revealed a significant difference in d', $\chi^2(1) =$

TABLE 1 Parameter estimations and goodness-of-fit statistics for the different models

		Stimulation condition			Overall model fit		
Model	**Parameter**	**Cathodal**	**Anodal**	**Sham**	χ^2	*df*	*p*
True memories							
EVSD	*d'*	0.88	0.81	0.95	647.90	12	<0.001
UVSD	*d'*	1.04	0.97	1.16	27.23	9	0.001
	S	1.33	1.34	1.46			
HTSD	*R*	0.21	0.21	0.26	170.93	9	<0.001
	F	0.59	0.51	0.58			
False memories							
EVSD	*d'*	0.71	0.58	0.66	156.52	12	<0.001
UVSD	*d'*	0.76	0.61	0.69	13.78	9	0.130
	S	1.24	1.23	1.28			
HTSD	*R*	0.11	0.11	0.11	69.14	9	<0.001
	F	0.53	0.39	0.47			

EVSD, equal variance signal detection; UVSD, unequal variance signal detection; HTSD, high threshold signal detection; d', memory strength; s, standard deviation of old items (true memories) and lure items (false memories); r, recollection; f, familiarity.

5.42, $p = 0.020$ $\eta^2 = 0.07$. In the second analysis step, we found that d' in the sham condition was numerically larger than in the anodal stimulation condition and smaller than in the cathodal simulation condition, although none of the two differences was significant, $\chi^2(1) = 1.44$, $p = 0.23$ and $\chi^2(1) = 1.20$, $p = 0.27$, respectively. Together, the results indicate that cathodal in comparison to anodal tDCS of the left ATL increased the number of false memories, with participants' performance in the sham stimulation condition numerically between the other two stimulation conditions, but not significantly different.[2]

3.1.3 | Side effects of tDCS

Side effects were rated on a visual analogue scale ranging from 0 (no sensation at all) to 100 (very strong sensation; see Table 2). Overall side effects were rated as mild with a tingling sensation being rated most noticeable across groups (mean = 31.92, *SD* = 26.97). Across time the side-effects were rated highest during the ramp-up phase (mean = 26.54, *SD* = 27.67) as compared to the plateau (mean = 23.72, *SD* = 21.99) or the ramp-down phase (mean = 19.23, *SD* = 21.43). In order to ensure that the experimental effects were not confounded by the experience of undergoing tDCS, we compared reports of side effects between the active and sham conditions. A MANOVA was calculated taking into account the main side-effects (i.e., tingling, burning, itching, headache, discomfort) simultaneously and comparing them across groups. Results showed no significant difference across groups (*Pillai's Trace* = 0.201, $F(2, 71) = 1.61$, $p = 0.11$).

4 | DISCUSSION

The results show that, for correct recollection of initially studied list words, both anodal and cathodal tDCS over the left ATL during recognition impeded memory performance. It should be noted that when compared to the sham condition, both active stimulation groups showed significant impairments. In addition, the results show that false recollection of concept lures was increased during cathodal tDCS compared to anodal tDCS over the left ATL. The active stimulation conditions were not significantly different to the sham condition. Nevertheless, an examination of effect sizes shows that tDCS had a relatively large negative effect on correct recollection, whereas the modulation of false memories was only of intermediate strength (Cohen, 1988; Hattie, 2008).

This pattern of results demonstrates the differential effect of tDCS on two separate processes. First, the reduced

[2]For the sake of comparability with earlier DRM recognition studies, we also calculated d' as an index of memory strength and λ as an index of response criterion (see Huff et al., 2015) on the individual level based on collapsed rating levels. Rating levels 1–3 were classified as "old" responses; rating levels 4–6 were classified as "new" responses. Three separate ANOVAs with the factor of stimulation (anodal vs. cathodal vs. sham) were calculated for d' for old items (0.99 vs. 1.08 vs. 1.15), d' for critical items (0.75 vs. 0.88 vs. 0.83) and λ (0.62 vs. 0.83 vs. 0.82). None of the three ANOVAs showed a significant stimulation effect, all *p*s > 0.05. We note however that the present group level ROC analysis is considered the more powerful analysis to detect small-to-medium sized stimulation effects in memory parameters (i.e., d'), because the parameters are based on theoretical memory models (i.e., the unequal-variance model) and the analysis has larger statistical power.

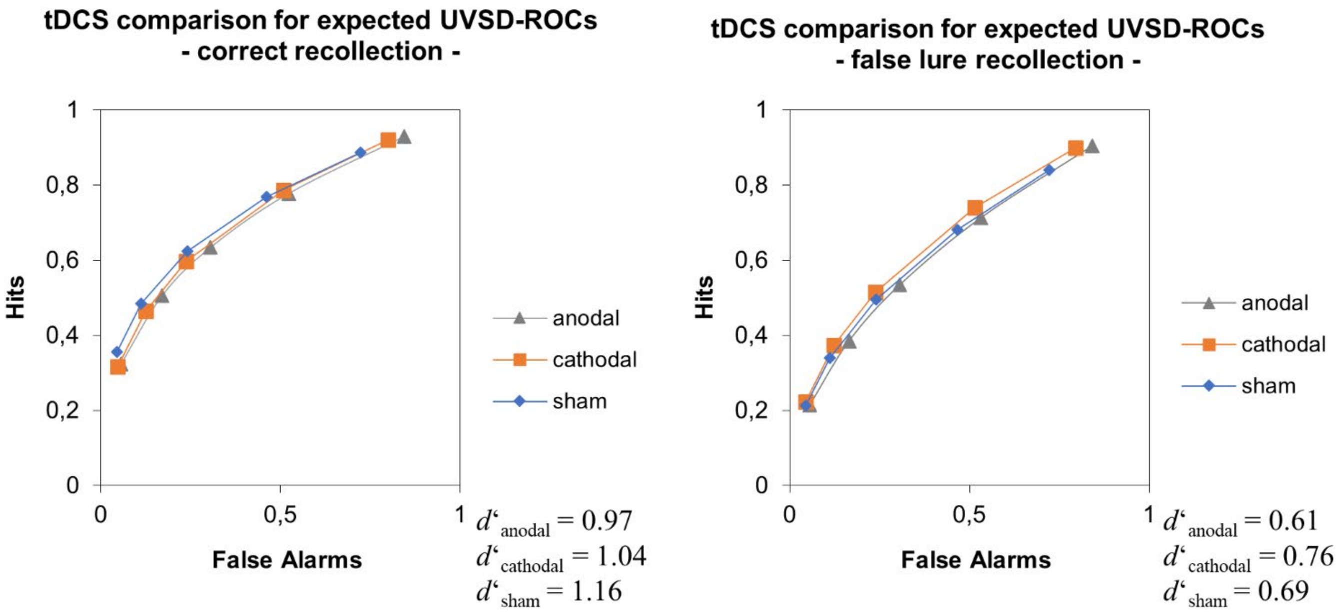

FIGURE 2 Visualization of results. The left panel shows the correct recollection of old items and the right panel the recollection of concept lures

TABLE 2 Side effects of the tDCS stimulation for all three conditions reported by the participants on a 0–100 scale; means and standard deviations (*SD*)

	Cathodal		Sham		Anodal	
Side Effect	**Mean**	***SD***	**Mean**	***SD***	**Mean**	***SD***
Itching	20.77	26.21	24.23	25.64	35.00	31.65
Tingling	22.31	23.38	34.23	28.17	39.23	27.27
Headache	4.23	8.09	11.15	20.46	12.31	22.50
Burning	5.00	11.40	20.77	29.52	13.08	24.94
Discomfort	5.77	9.86	13.85	21.74	17.69	22.15
Ramp-up	17.31	18.88	28.46	28.94	33.85	31.88
Plateau	23.08	22.94	18.08	16.74	30.00	24.66
Ramp-down	15.77	18.80	22.69	21.64	18.82	23.82

memory performance for the originally learned items was affected in a polarity-independent way that can be explained by the change of signal-to-noise ratio in the left ATL. Thus, tDCS of both polarities may have disturbed the recollection process by adding noise to the system (Miniussi et al., 2013). Second, lure recollection was affected by the stimulation in a polarity-dependent way. While not all pairwise comparisons were significant, analysis revealed that both cathodal and anodal stimulation led to significantly different results with the sham condition taking a spot between the two. Taking the performance in the sham condition as a control condition, the results suggest that cathodal tDCS increased false lure recollection (i.e., increased the DRM effect), whereas anodal tDCS decreased false lure recollection (i.e., reduced the DRM effect). Based on this, two alternative interpretations are possible. Given that the left ATL has been implicated in monitoring and exerting inhibitory control over the task-irrelevant associations, it seems plausible that anodal tDCS enhanced and cathodal stimulation perturbed this process (Abe, 2012; Conway & Fthenaki, 2003; Jung et al., 2017; Wimber et al., 2008). Specifically, one could speculate that anodal tDCS increased overall activity and consequently lifted background noise above a meaningful processing threshold. Conversely, cathodal tDCS might have reduced overall activity and thus mainly reduced the signal level below a meaningful processing threshold. Alternatively, the weighting of the (goal-irrelevant) associations between the words was altered by the stimulation. This interpretation aligns with the CSC framework (Ralph et al., 2016), which maintains that the ATL is essential to the formation and representation of concepts; perturbation of this process may have altered the concept retrieval process. However, the exact role of the ATL in the DRM task and the specific process(es) modulated in the present study still remain somewhat unclear. While the present results fit the activation-monitoring-framework as well as the CSC framework and it seems plausible that the stimulation impacted the activation of learned items as well as concept lures, future research is needed to provide more support for this hypothesis Thus, tDCS might be able to modulate the constructive memory process and directly change human perception.

Importantly, the effects of the present study were evident during stimulation over the recognition phase of the task. Thus, in the future non-invasive brain stimulation tools (if made reliable on an individual level) could be used in real-life applications such as criminal investigations. An individual might be able to recognize more correct and less incorrect information due to the influence of tDCS. Furthermore, other areas for stimulation should be explored in the future. For example, past research has shown that the prefrontal cortex plays a role in false memories due to its role in monitoring cognitive processes (Chadwick et al., 2016; Straube, 2012). Thus, a future study could aim to disentangle the activation and monitoring processes underlying illusory memories by targeting the ATL as well as the prefrontal cortex with NIBS during DRM task performance. Stimulation of the ATL in both encoding and recognition phases should impact the activation of items within memory. Conversely, stimulation of the prefrontal cortex only during the recognition phase should influence monitoring.

Needless to say, the present study is not without limitations. First, the sample size of the study could be regarded as too low given the between-subject design and may not have provided sufficient power to detect small effects. With that being said, to ensure that measurements were as accurate as possible a total of 40-word lists were used per participant. Nevertheless, future studies should try to replicate and extend our results using a larger sample (for the principle of aggregation see Rushton et al., 1983; but see also Brand et al., 2011). Second, tDCS is not reliable on an individual level and the inter-individual differences between participants are usually at least moderate in tDCS studies (Friehs et al., 2020; Krause & Cohen Kadosh, 2014). This implies that, while stimulation may have an effect on one individual, another might exhibited the reverse effects or the individual might not be affected at all. Third, the present results are not necessarily applicable to real-life situations, as DRM effects have been shown to only weakly correlate with other false memory paradigms (Bernstein et al., 2018; Ost et al., 2013). Future studies should explore the effect of tDCS on misinformation paradigms in general and explore the real-life applications. Fourth, analysis of the side-effects showed small differences between groups. However, critically, the analysis revealed no overall significant difference between conditions; thus indicating that the results cannot be explained in terms of experiential differences. Further, this stimulation procedure has been used multiple times before across a variety of cognitive tasks (for similar procedures see Friehs et al., 2019; Friehs & Frings, 2019a, 2019b, 2020). The sham stimulation condition and control conditions in tDCS research have been a point of contention. For example, from an experimental standpoint, within-subject designs are preferable to reduce the influence of inter-individual differences. Yet, they bear the risk of ineffective blinding, as tDCS is associated with distinct physical sensations. Participants' beliefs about specific stimulation conditions and potential side effects should at least be assessed with standard questionnaires after the experiment (e.g., Fertonani et al., 2010; Poreisz et al., 2007). In tDCS studies, sham stimulation is usually realized by ramping up the current to target intensity for 10–30 s and immediately ramping it down again. This produces some cutaneous sensations such as tingling, itching or burning in the beginning, when they are also strongest for effective tDCS, with the aim of making effective and sham tDCS indistinguishable (Gandiga, Hummel, & Cohen, 2006). However, recent evidence shows that, even if low stimulation intensities are used, participant blinding is compromised (Greinacher, Buhôt, Möller, & Learmonth, 2019; Turi et al., 2019). Here it should be noted that we directly asked about the participants' experience and did not find an overall statistically significant difference between the stimulation conditions, suggesting that participants did not detect a difference. In contrast to a sham condition, an active control condition (i.e., active stimulation over an area not involved in the to-be-modulated process) may be implemented. Some authors even suggest that in some circumstances, not using a sham condition at all may have few to no drawbacks (e.g., Friehs et al., 2019; Frings et al., 2018). Fifth, the results of the present study and their interpretation are somewhat limited because of the potential of network-wide effects of the stimulation. Although the current flow simulation (Figure 1) shows that employed stimulation causes a focal stimulation of the left ATL, knock-on effects cannot be ruled out. Further, there is evidence that different structures within the left ATL are responsible for different processes (Ralph et al., 2016), but tDCS is not capable of sufficiently targeted and focal stimulation to distinguish between functional areas within the ATL. Future high-definition (HD) tDCS or TMS research may like to look into that possibility.

To conclude, we complement previous neuromodulation studies on the DRM task (e.g., Boggio et al., 2009; Pergolizzi & Chua, 2015). This study is the first to employ tDCS over the left ATL during the recognition phase of the DRM task and results demonstrate a significant difference between anodal and cathodal tDCS conditions on performance in the DRM task. Specifically, performance on correct recognition was impaired during both anodal and cathodal tDCS; however, false memories were differently affected by anodal and cathodal stimulation. Further, it should be noted that while the difference between anodal and cathodal tDCS conditions was significant, the difference between either of them and the sham condition was not. Nevertheless, these results provide further evidence for the importance of the left ATL for semantic processing in memory. Future studies may like to replicate and extend these results. For example, the interaction between prefrontal areas—in their monitoring function—and the left ATL—in its function as a semantic hub (see Ralph et al., 2016)—has high priority to be examined in future work. Additionally, (dis)similarities in the underlying processes in different false memory paradigms and the transferability of findings to non-laboratory settings need to be explored, before this knowledge can be transferred to everyday life.

CONFLICT OF INTEREST

The authors have no conflicts of interests to disclose.

AUTHOR CONTRIBUTIONS

MAF and BP conceptualized the study and methodology. MAF was involved in data curation, project administration and data gathering. BP and MAF were involved in the formal analysis. All authors were involved in validation, visualization, and the writing as well as the editing of the manuscript.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

All data and all materials are uploaded to OSF. They can be accessed via https://doi.org/10.17605/OSF.IO/X5QAS.

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