Effect of prefrontal and parietal tDCS on learning and recognition of verbal and non-verbal material

Aurélie L. Manuel, PhD, Armin Schnider, MD

Laboratory of Cognitive Neurorehabilitation, Division of Neurorehabilitation, Department of Clinical Neurosciences, University of Geneva and Univesity Hospital of Geneva, Switzerland

Correspondence:

Dr. Aurélie Manuel

Service de Neuroréducation

Hôpitaux Universitaires de Genève

26, av. de Beau-Séjour

1211 Geneva 14, Switzerland

Tel.: +41-22-372 3647

Fax: +41-22-372 3705

E-mail: aurelie.manuelstocker@hcuge.ch

Abstract

Objective: Information learned in a spaced way is usually better recognized than information learned in a massed way. The brain mechanisms underlying this spacing effect remain unclear.

Methods: We applied anodal transcranial direct current stimulation (tDCS) to the left and right prefrontal (PFC) or posterior parietal (PPC) cortices to study how stimulation influences learning and retrieval of information, as evidenced by item recognition and the spacing effect, and whether the effects are lateralized according to stimulus material and site of stimulation. We **devised** a continuous recognition task with verbal and non-verbal stimuli repeated either immediately or after a delay. Stimulus recognition was tested 30minutes later.

Results: There was a spacing effect for both materials, which, however, was not modulated by tDCS. Nonetheless, tDCS differentially impacted memory retrieval regardless of repetition mode during learning: tDCS over the PPC during learning enhanced recognition of non-verbal material regardless of side of stimulation, while tDCS over the left PFC decreased recognition regardless of material.

Conclusions: The PPC seems to be involved specifically in the mnemonic treatment of non-verbal material whereas the left PFC specifically influences learning irrespective of stimulus material.

Significance: Prefrontal and posterior parietal cortices follow different lateralization rules in recognition memory.

Keywords: Episodic memory, encoding, retrieval, transcranial direct current stimulation, posterior parietal, prefrontal, lateralization.

1. Introduction

Stimuli presented in immediate succession during learning (massed repetition) are less well retained in memory than stimuli repeated after a delay (spaced repetition) (Nielsen-Bohman and Knight, 1994, Chao et al. , 1995, Kim et al. , 2001, Kim et al. , 2008). This effect is referred to as the spacing effect (Ebbinghaus, 1885/1992). Spacing effects have been reported with verbal and non-verbal and with meaningful and meaningless material (Challis, 1993, Mammarella et al. , 2002, Russo and Mammarella, 2002, Russo et al. , 2002).

However, the brain mechanisms, including the hemispheric contributions, underlying the spacing effect remain unclear. While verbal massed repetition has been variably shown to activate the cingulate cortex (Kim et al. , 2001, 2008) or a left-lateralized parietal network (Manuel and Schnider, 2016), non-verbal massed repetition activates the left medio-temporal lobe (James et al. , 2009, Nahum et al. , 2011, Nahum et al. , 2015) or right prefrontal cortex (Manuel and Schnider, 2016).

The medio-temporal and prefrontal regions of the brain are critical areas for episodic memory (Simons and Spiers, 2003, Squire et al. , 2004). Several PET and fMRI studies also reported posterior parietal cortex (PPC) activation in episodic memory tasks (Rugg et al. , 2002, Wagner et al. , 2005, Cabeza et al. , 2008, Ciaramelli et al. , 2010). Hemispheric lateralization was repeatedly observed: There was lateralization to the left prefrontal cortex (PFC) and medio-temporal lobe (MTL) in studies using verbal **information** and right-lateralization for non-verbal stimuli (Kelley et al. , 1998, Wagner et al. , 1998). On a conceptual level, the hemispheric encoding retrieval asymmetry model (HERA) proposed that the left PFC would be **essential for encoding, the right PFC for retrieving verbal (Shallice et al. , 1994) as well as non-verbal material (Tulving et al. , 1994)**. Transcranial magnetic stimulation (TMS) studies yielded mixed results. TMS to the left PFC interfered with encoding of pictures of complex scenes whereas right PFC stimulation dampened retrieval, a pattern in favour of the HERA

model (Rossi et al. , 2001, Floel et al. , 2004, Rossi et al. , 2006). Another study showed that **TMS over the left PFC interfered with encoding of verbal material and encoding of non-verbal material was disrupted** by stimulation of right PFC, speaking in favor of a material specific lateralization in the PFC (Floel et al. , 2004). Finally, Sandrini et al. (2003) showed that repetitive transcranial magnetic stimulation (rTMS) to the left and the right PFC interfered with encoding of word pairs.

Although repeatedly reported in lesion studies (Kessels et al. , 2002, Ally et al. , 2008), lateralization of PPC function is less consistent in neuroimaging studies and TMS studies. Nagel et al. (2013) reported a left hemispheric lateralization for verbal memory, whereas Wagner et al. (2005) demonstrated left PPC activation in old/new recognition tasks with verbal and non-verbal stimuli. Furthermore, while Manenti et al. (2010) reported disruption of verbal memory retrieval following TMS over the left PPC, Rossi et al. (2006) observed no such effect.

Here we tested the influence of transcranial direct current stimulation (tDCS) applied over left and right PFC and PPC during encoding of verbal and non-verbal material and its effect on delayed retrieval, in particular its effect on the spacing effect. tDCS is a well-tolerated neuromodulation technique (Nitsche et al. , 2003, Brunoni et al. , 2011) where a low intensity electrical current is applied to the scalp to temporarily modulate cortical excitability. Anodal polarization **augments** cortical excitability while cathodal polarization **diminishes** it (Paulus, 2003, Nitsche and Paulus, 2011, Dayan et al. , 2013, Parkin et al. , 2015). The existence of cortical excitability modulations have been initially shown in the human motor cortex (Nitsche and Paulus, 2000, 2001) and visual cortex (Antal et al. , 2003), and only recently in higher-order cognitive functions such as memory (e.g. Shin et al. , 2015). tDCS studies have demonstrated enhanced retrieval of non-verbal material following anodal stimulation of the right PFC (Chi et al. , 2010) and improved verbal memory following anodal tDCS over the

left PFC (Javadi and Cheng, 2013). Anodal tDCS over the left parietal cortex has also been shown to **enhance** verbal memory (Jacobson et al. , 2012, Jones et al. , 2014).

To assess how left and right PFC and PPC tDCS during encoding modulate verbal and non-verbal memory retrieval, including the spacing effect, we devised a continuous recognition task **comprising non-verbal (meaningless geometric designs) and verbal stimuli (non-words) repeated either immediately or after a delay**. Memory retrieval was tested 30 minutes later.

We hypothesized that left PFC or PPC stimulation would improve recognition of verbal material whereas right PFC or PPC stimulation would enhance non-verbal mnemonic processing.

2. Methods

2.1. Participants

Twenty-eight healthy, French-speaking, right-handed participants were included in the study. Two participants were excluded as they did not complete the whole experiment. The remaining 26 participants took part in the study composed of two separate experiments: half of the subjects were attributed to PPC stimulation group ($n=13$, aged 24 ± 5 ; seven men), the other half to the PFC stimulation group ($n=13$, aged 23 ± 3 ; four men). The two groups did not significantly differ regarding gender distribution ($\chi^2(1) = 1.42, p = 0.23$) or age ($t_{(24)} = 0.68, p = 0.51$). **Participants gave written consent to take part in the study and were remunerated for their participation**. No participant had a history of neurological or psychiatric illness. The procedures were **validated** by the Ethics Committee of the Canton of Geneva.

2.2. Experimental design

For this single-blind, sham-controlled study, participants were recruited separately for both experiments. In the first experiment, participants received tDCS over the posterior parietal

cortex and in the second experiment they were stimulated over the prefrontal cortex.

Stimulation was delivered during the continuous recognition task (learning task). The delayed recognition task performed 30 minutes later was stimulation-free. Each participant completed three sessions: left anodal, right anodal and sham. Order of sessions was randomized within subjects and sessions were planned with at least one week between sessions to avoid carry-over effects of tDCS or the task.

2.3. Stimuli

Stimuli were non-words (verbal material) and abstract geometrical shapes (non-verbal material). The non-words were composed of a series of five letter meaningless words (Arial, font size 100) pronounceable according to French pronunciation rules. The non-verbal material consisted of black and white stimuli representing meaningless geometric designs. These stimuli were created with a program we devised which allows producing random abstract geometric pictures. We only included stimuli that touched the 4 borders of the frame (size 8.7x5.3cm) and which were composed of at least 4 different elements. To assess whether visual complexity differed among the chosen set of abstract geometric designs, an independent group of 11 participants were asked to rate visual complexity using a 7-point scale (“very simple” to “very complex”). Rating of mean visual complexity did not differ between the two learning blocks (3.6 ± 1 block 1; 3.6 ± 0.9 block 2) or the delayed recognition task (3.7 ± 0.9 ; $F_{(2,149)} = 0.4$, $p = 0.65$).

We used meaningless stimuli to separate verbal and non-verbal components and increase the likelihood of hemispheric lateralization as it has indeed been shown that encoding of meaningful pictures may elicit verbal processing and thus prevent non-verbal processing from happening (Kelley et al. , 1998, Golby et al. , 2001). Similarly, processing real words may

trigger image-based representations of word reading and thus be less specific to the left hemisphere (Beisteiner et al. , 1996, Binder et al. , 2005, Marinkovic et al. , 2014).

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2.4. Learning task

Participants performed **two blocks of a continuous recognition task** (Fig. 1). Each block was composed of **50 abstract geometrical figures** (Non-verbal material, NV) and **50 non-words** (Verbal material, V). **Each stimulus was repeated either immediately after the initial presentation** (One-back items, n=50; 25 V, 25 NV) or **following** nine intervening items (Ten-back items, n=50; 25 V, 25 NV). **The second block consisted of the same task but with a new set of stimuli.** In total, there were 100 trials for **initial** presentation of non-verbal stimuli (NewNV), 100 trials for **initial** presentation of verbal stimuli (NewV) and **50 trials for each of the repeated conditions: immediate non-verbal repetition (One-back NV), immediate verbal repetition (One-back V), spaced non-verbal repetition (Ten-back NV) and spaced verbal repetition (Ten-back V).**

Stimuli were presented on a 17-inch screen positioned at 70 cm from the participant (visual angle ~ 2°). Stimuli were showed for 1000 ms, followed by a 2000 ms inter-stimulus interval displaying a fixation cross. Participants were asked to respond on a response box using their right, dominant hand. Initial stimulus presentation required a right middle finger button press and stimulus repetition required a right index finger button press. Each block lasted about 10 minutes, separated by a break of 2 minutes.

2.5. Delayed recognition task

To test for long-term memory retention, participants were tested on a delayed recognition task 30 minutes after completing the learning task. This task comprised the totality of the 200

stimuli previously presented in the initial learning task (50 pOneV, 50 pOneNV, 50 pTenV, 50 pTenNV) plus 100 new items (50 pNewV, 50 pNewNV) randomly presented. Task duration was 15 minutes. Participants had to indicate whether stimuli had appeared in the learning task or not. Stimuli were the same for the three sessions. There was a one-week interval between each session to ensure a proper tDCS and memory wash-out.

2.6. Data analysis

A series of 2 x 3 x 2 x 3 mixed-model repeated measures ANOVAs with between factor Group (Parietal, Prefrontal) and within factors tDCS (Anodal L, Anodal R, Sham), Material (Verbal, Non-verbal) and Condition (New, One-back, Ten-back) were performed on accuracy (percentage of correct responses) and response time. Significant interactions were followed by simple effects at each combination of levels of the other factors. Whenever significant, post-hoc Bonferroni corrected t-tests were performed. A measure of the effect size of each result is provided with the partial eta square (η_p^2).

The spacing effect index reflects the advantage for greater recognition in the delayed recognition task of stimuli previously presented in a spaced compared to massed way and was calculated separately for verbal and non-verbal material as following: “%Hits pTen – %Hits pOne” which is the difference between correctly identified stimuli which have been repeated after a delay in the learning task (Hits pTen) and correctly identified items that were presented in immediate succession in the learning task (Hits pOne). Statistical differences were assessed with a 2 x 2 x 2 mixed-model repeated measures ANOVA with between factor Group (Parietal, Prefrontal) and within factors tDCS (Anodal L, Anodal R, Sham) and Material (Verbal, Non-verbal).

2.7. Questionnaires

During the 30 min break between the learning task and the delayed recognition task, subjects completed questionnaires on side effects (Brunoni et al. , 2011) and two ad-hoc questionnaires on health status and task difficulty.

Following each tDCS session, participants evaluated the intensity of perceptual sensation items with a 4-point rating scale (1 = absent, 4 = severe) and indicated if the sensation was related to the stimulation or not with a 5-point rating scale (1 = none, 5 = definite). The questionnaire included the following possible tDCS side-effects: **headache, scalp and neck pain, tingling, burning sensation, itching, skin redness, trouble concentrating, sleepiness, acute mood change and others**. This questionnaire enabled us to measure possible differences in participants' awareness between stimulation conditions. In addition following each session, participants filled in a questionnaire assessing task difficulty of the delayed recognition task with a 5-point scale (1 = not difficult, 5 = very difficult). Differences between conditions were assed with repeated measure ANOVAs with factors Group (Parietal, Prefrontal) and tDCS (Anodal Left, Anodal right, Sham).

2.8. Transcranial direct current stimulation

Direct electrical current was delivered by a battery-driven NeuroConn DC brain stimulator (NeuroConn, Ilmenau, Germany) using a pair of 35 cm² rubber electrodes enclosed in saline-soaked sponges. In the parietal group, the anode **electrode** was placed over P3 (left PPC) or P4 (right PPC) according to the 10-20 EEG system. The cathode was placed over the contralateral supraorbital region. In the prefrontal group, the anode was placed over F3 (left dorsolateral prefrontal cortex; DLPFC) or F4 (right DLPFC). The cathode was placed over the contralateral supraorbital region. Both setups have been used successfully in memory

studies (Fregni et al. , 2005, Javadi and Cheng, 2013, Manenti et al. , 2013). As a note of caution, it may be noted that in bilateral electrode montages with variable distance between the anode and the cathode, the current may not be distributed in an equal way in the two montages (Bikson et al. , 2012, Ruffini et al. , 2013).

A direct current of 1mA with a fade-in and fade-out of 8 s was delivered for 24 min for the anodal stimulation conditions. The learning task started 4 minutes after the onset of the stimulation and lasted 20 minutes to ensure that tDCS had reached maximum effect at the start of the experiment (Nitsche and Paulus, 2000). For the sham condition, the electrodes were placed as for active stimulation, but the current was turned off after 30 seconds. The participants thus felt the sensation of electrical stimulation under the electrodes. This procedure was shown to reliably blind participants (Gandiga et al. , 2006). Current densities for the three sessions were maintained below the safety limit of 0.052 mA/cm² (Nitsche et al. , 2003, Iyer et al. , 2005) and the impedance was controlled by the device and kept low (<10 Ω) for all stimulation sessions.

3. Results

3.1. Questionnaires

All participants well tolerated the tDCS and reported only minor side effects. Repeated measure ANOVA with factor Group and tDCS revealed that participants in the sham condition reported less side effects than in the both stimulation conditions ($F_{(1, 48)} = 19.68, p < 0.01$). However, there were no significant differences in perceived difficulty between groups for any of the stimulation conditions ($p > 0.33$).

----- Table 1 here -----

3.2. Learning task

Repeated measures ANOVAs on **accuracy (percentage of correct responses)** and response time revealed main effects of Condition: immediate repetitions (One-back) were processed faster ($F_{(2,48)} = 126.09, p < 0.01, \eta_p^2 = 0.84$) and more accurately ($F_{(2,48)} = 20.60, p < 0.01, \eta_p^2 = 0.46$) than new items (New) or spaced repetitions (Ten-back). Regarding accuracy, there was no interaction with tDCS (all $p > 0.19$) or between-subject effects ($F_{(1,24)} = 0.001, p = 0.97, \eta_p^2 < 0.01$). For response time there was no interaction with tDCS (all $p > 0.27$) or between-subject effects ($F_{(1,24)} = 0.85, p = 0.37, \eta_p^2 = 0.03$). Percentage accuracy and response time for all conditions are reported in Table 1.

----- Figure 2-----

3.3. Delayed recognition task

Regarding accuracy, repeated measure ANOVA indicate a spacing effect: Participants **showed greater accuracy** in recognizing items repeated after a delay in the learning task (pTen) and new items of the delayed recognition task (pNew) than items repeated in immediate succession (pOne) during learning ($F_{(2,48)} = 29.53, p < 0.01, \eta_p^2 = 0.55$; Table 1). Furthermore, there was a tDCS x Material x Group interaction ($F_{(2,48)} = 4.91, p = 0.01, \eta_p^2 = 0.17$; Fig. 2A) and a Material x Condition x Group interaction ($F_{(2,48)} = 4.80, p = 0.01, \eta_p^2 = 0.17$). Post-hoc tests revealed that the tDCS x Material x Group interaction was driven by specific effects of tDCS in the PFC group and specific effects of material in the PPC group. First, in the PPC group, accuracy was greater for non-verbal compared to verbal stimuli after left ($p = 0.01$) and right ($p = 0.04$) PPC anodal stimulation. There were no simple effects for factor Group at each combination of levels of other factors (all $p > 0.08$), nor between-subject

effects ($F_{(1,24)} = 0.22, p = 0.88, \eta_p^2 = 0.01$). Secondly, anodal tDCS over the left prefrontal cortex worsened performance for verbal stimuli compared to right prefrontal tDCS ($p = 0.03$) or sham ($p = 0.03$) and a trend (considering the Bonferroni correction) for non-verbal stimuli in comparison to sham ($p = 0.056$).

Response time was faster for items previously repeated after intervening items than for new (in the delayed recognition task) or items repeated in immediate succession during learning (Main effect of Condition: $F_{(2,48)} = 4.79, p = 0.01, \eta_p^2 = 0.16$) and faster for non-verbal compared to verbal stimuli (Main effect of Material: $F_{(1,24)} = 7.62, p = 0.01, \eta_p^2 = 0.24$). There were no significant interactions (all $p > 0.07$). Between-subjects effects were not significant ($F_{(1,20)} = 3.42, p = 0.08, \eta_p^2 = 0.13$).

Regarding the spacing effect index (%Hits pTen – %Hits pOne), repeated measure ANOVA revealed that the magnitude of the spacing effect was not modulated by tDCS ($F_{(2,48)} = 0.70, p = 0.50, \eta_p^2 = 0.03$), Material ($F_{(1,24)} = 2.02, p = 0.21, \eta_p^2 = 0.08$), Group ($F_{(1,24)} = 0.75, p = 0.39, \eta_p^2 = 0.03$) or by an interaction between these factors ($p > 0.49$).

4. Discussion

This study confirms the **existence** of a spacing effect **for non-verbal and verbal material**, yet without any tDCS-related modulation of its magnitude. Rather, tDCS differentially impacted recognition memory 30 minutes later: Anodal tDCS over the posterior parietal cortex enhanced performance for non-verbal stimuli regardless of side of stimulation. Anodal tDCS over the left prefrontal cortex decreased recognition for both materials. tDCS did not influence performance during the learning task, in which accuracy was very high (82-98% correct).

Our results highlight the complexity of hemispheric lateralization in PPC and PFC. Our first finding **confirms** the **role** of the posterior parietal region in episodic memory, as indicated by **neuroimaging** studies (Wagner et al. , 2005, Skinner and Fernandes, 2007, Simons et al. , 2008). Previous tDCS and TMS studies yielded conflicting results: Stimulation of the left PPC either enhanced (Jacobson et al. , 2012, Jones et al. , 2014) or disrupted verbal memory (Manenti et al. , 2010). Using pronounceable but meaningless words (non-words), we obtained no effect of PPC stimulation. In contrast, PPC stimulation on both sides enhanced recognition of non-verbal material, a finding compatible with the parietal lobes' role in processing spatial information (Andersen, 1997, Duhamel et al. , 1997, Burgess, 2008) with little hemispheric specificity. The non-verbal stimuli used in this study were complex, meaningless, geometric designs inciting spatial processing.

Our second finding supports the role of the left PFC during encoding of verbal stimuli (Shallice et al. , 1994, Fletcher et al. , 1995, Nyberg et al. , 1996) and a trend for non-verbal stimuli (Tulving et al. , 1994, Grady et al. , 1995, Haxby et al. , 1996) presumably by maintaining information required to form episodic traces (Rossi et al. , 2011). This result is in accordance with previous studies showing that TMS to the left DLPFC interfered with encoding of verbal and non-verbal stimuli (Rossi et al. , 2001, Floel et al. , 2004, Rossi et al. , 2006). In our study, left PFC stimulation during learning led to a drop in performance during later recognition testing. While the effect is clear, our study does not allow us to attribute it unequivocally to interference during encoding. tDCS has after-effects, which may still have been active during the recognition test (Nitsche and Paulus, 2000, 2001).

The negative effect of tDCS on learning and recognition appears to be at odds with the **most** tDCS studies, which associate anodal stimulation to enhancement of cognitive performance (Javadi et al. , 2012, Javadi and Walsh, 2012, Javadi and Cheng, 2013). However, recent studies also report a **drop in** performance **following** anodal tDCS (Ferrucci et al. , 2008, Jones

and Berryhill, 2012, Kaminski et al. , 2013, Zwissler et al. , 2014, Schaal et al. , 2015) or improvements following cathodal tDCS (Smirni et al. , 2015). A recent tDCS study reported a significant decrease in performance in an old/new recognition task following anodal tDCS over the left PFC during encoding of pictures (Zwissler et al. , 2014). Ferruci et al. (2008) reported a detrimental effect of **anodal tDCS stimulation over the PFC during a task assessing working memory**. Anodal tDCS over the prefrontal cortex may possibly increase neural signal and noise (Antal et al. , 2004, Dockery et al. , 2009, Miniussi et al. , 2013) during the encoding of verbal and non-verbal stimuli, resulting in weaker recognition in the delayed recognition task. Furthermore, normal variations in inter-individual anatomy and electrode montages determine the current flow distribution and may account for the fact that different electrode montages **may lead to different patterns of current flow across the brain** (Bikson et al. , 2012, Datta et al. , 2013, Truong et al. , 2013, Parazzini et al. , 2015, Labruna et al. , 2016).

We obtained lateralized effects only with prefrontal, but not with parietal stimulation. While the electrode setup was standard, it is possible that this result was influenced by the distance between the electrodes, which was longer in the parietal stimulation group. The electrical field reaches its maximum intensity towards the middle between the two electrodes (Bikson et al. , 2012, Ruffini et al. , 2013) so that the stimulation presumably extends beyond the site under the anode. This caveat does not put into question the specificity of the effects observed with the two electrode setups in this study. High density electrode montages would allow for more focal stimulation effects in the future (Bikson et al. , 2012, Ruffini et al. , 2013).

Although the behavioural results confirm previous reports showing a spacing effect for a multitude of learning materials (Cornoldi and Longoni, 1977, Challis, 1993, Braun and Rubin, 1998, Russo et al. , 1998, Mammarella et al. , 2002, Russo et al. , 2002, James et al. , 2009), its magnitude was not modulated by tDCS nor were there tDCS-induced differences **in**

processing immediate versus spaced repetitions. One possible explanation is that, tDCS may not have targeted the brain regions involved in processing immediate and spaced repetitions, despite their known role in episodic memory. Neuroimaging studies indeed reported differential activations between immediate and spaced repetitions in various brain regions including left and right prefrontal, parietal, temporal, occipital or even cingulate cortex (Kim et al. , 2008, James et al. , 2009, Zhao et al. , 2015, Manuel and Schnider, 2016). Comparison with previous tDCS or TMS studies is delicate as they did not analyze recognition of stimuli learnt in a spaced and massed way separately (Javadi and Walsh, 2012, Manenti et al. , 2013) or they applied tDCS over prefrontal or posterior parietal regions before encoding (Jacobson et al. , 2012), during recognition (Manenti et al. , 2013, Pergolizzi and Chua, 2015, Pisoni et al. , 2015) or during reactivation (Javadi and Cheng, 2013), but not during encoding –with influence potentially extending to storage and recognition- as done in the present study. Hence, effects of stimulation may differ depending on when it is applied (Brunoni et al. , 2012, Hill et al. , 2016). A study comparing delayed recognition of new and old pictures, with anodal tDCS applied over the left PFC during encoding, showed a decrease in performance (Zwissler et al. , 2014) - a result similar to our study.

5. Conclusion

Using tDCS, our study indicates that left prefrontal cortex specifically influences memory processing regardless of material, while the posterior parietal cortices influence mnemonic processing of non-verbal, but not verbal, material. The study provides evidence that functional hemispheric lateralization does not follow the same rules throughout the brain.

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Figure Legends

Figure 1: Task design.

A. Participants performed two blocks of a continuous recognition task containing verbal (non-words, V) and non-verbal (meaningless geometric designs, NV) stimuli. Stimuli were presented (New) and immediately repeated (One-back; One-backNV, One-backV) or repeated after a delay (Ten-back; Ten-backNV, Ten-backV). The two blocks were composed of different stimuli and separated by a 2 min break. tDCS was applied during the continuous recognition task only. **B.** Thirty minutes after the completion of task A, participants performed a delayed recognition task comprising all the stimuli *previously presented* (pOneNV, pOneV, pTenNV, pTenV) plus new non-words (pNewV) and new meaningless designs (pNewNV).

Figure 2: Behavioral results.

A. Accuracy, **B.** response time in the delayed recognition task following anodal tDCS over left (AL), right (AR) hemisphere and during sham (S) stimulation for both materials. The head models indicate the electrode position for the different conditions, with black electrodes (+) indicating the position of the anode and white electrodes (-) the position of the cathode. The left part shows results of the prefrontal group, the right part refers to the parietal group. Responses for New, One-back and Ten-back are collapsed. Bars show means and standard error mean. * $p < 0.05$, ** $p < 0.01$. The grey * indicates a trend considering the Bonferroni correction.

A Continuous recognition task

--- 30 min ---

B Delayed recognition task

A. Accuracy **B. Response time**

A. Learning task			Verbal			Non-verbal		
			New	One-back	Ten-back	NewV	One-Back	Ten-back
Accuracy	parietal	Anodal left	95±1	99±1	87±2	95±1	98±1	90±2
		Anodal right	88±5	92±5	84±5	87±5	90±5	85±5
		Sham	95±1	98±1	86±3	93±2	99±1	89±4
	prefrontal	Anodal left	93±2	96±3	83±5	95±1	93±3	82±5
		Anodal right	93±2	97±1	89±3	95±2	96±2	86±3
		Sham	95±1	97±1	86±3	95±1	96±1	85±4
RT	parietal	Anodal left	795±59	646±59	793±55	812±63	646±62	775±63
		Anodal right	762±64	620±55	745±59	775±64	617±57	748±59
		Sham	771±53	649±54	770±51	786±50	649±56	764±51
	prefrontal	Anodal left	728±34	595±20	739±23	709±26	604±22	739±26
		Anodal right	719±27	586±14	714±17	711±23	581±19	722±20
		Sham	721±33	589±20	739±25	727±30	596±19	726±24

B. Delayed recognition task			Verbal			Non-verbal		
			New	One-back	Ten-back	NewV	One-Back	Ten-back
Accuracy	parietal	Anodal left	76±4	58±3	66±3	79±4	63±4	77±3
		Anodal right	80±3	53±5	61±5	79±3	59±5	72±5
		Sham	82±3	57±3	66±4	81±3	57±5	70±4
	prefrontal	Anodal left	76±5	55±6	65±5	86±2	50±4	63±6
		Anodal right	80±4	61±5	74±5	86±3	54±5	70±5
		Sham	79±3	59±6	71±5	87±2	60±5	71±5
RT	parietal	Anodal left	885±53	890±26	888±56	916±64	865±56	847±56
		Anodal right	927±57	945±72	900±66	933±61	877±66	851±54
		Sham	948±56	918±67	917±56	932±51	896±64	867±55
	prefrontal	Anodal left	822±54	815±26	783±21	766±28	803±31	767±28
		Anodal right	811±52	797±28	755±20	777±37	799±31	753±31
		Sham	797±44	811±40	786±32	786±34	788±39	753±31

Table 1. Behavioral results (mean ± SEM) for the learning task and delayed recognition task.