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Research Report

Visual memory improved by non-invasive brain stimulation

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ABSTRACT

Our visual memories are susceptible to errors, but less so in people who have a more literal cognitive style. This inspired us to attempt to improve visual memory with non-invasive brain stimulation. We applied 13 min of bilateral transcranial direct current stimulation (tDCS) to the anterior temporal lobes. Our stimulation protocol included 3 conditions, each with 12 neurotypical participants: (i) left cathodal stimulation together with right anodal stimulation, (ii) left anodal stimulation together with right cathodal stimulation, and (iii) sham (control) stimulation. Only participants who received left cathodal stimulation (decrease in excitability) together with right anodal stimulation (increase in excitability) showed an improvement in visual memory. This 110% improvement in visual memory was similar to the advantage people with autism, who are known to be more literal, show over normal people in the identical visual task. Importantly, participants receiving stimulation of the opposite polarity (left anodal together with right cathodal stimulation) failed to show any change in memory performance. This is the first demonstration that visual memory can be enhanced in healthy people using non-invasive brain stimulation.

1. Introduction

> *"In a world of constantly changing environment, literal recall is extraordinarily unimportant…memory appears to be far more decisively an affair of construction rather than one of mere reproduction."*
>
> (Bartlett, 1932) *Remembering*

Our memories are not literal representations of the past (Bartlett, 1932; Loftus, 2003; Roediger and McDermott, 1995; Schacter and Addis, 2007). Instead, "facts" are unconsciously constructed to fit our schemata, existing mental representations of the world. Many have argued that this 'construction' is an integral aspect of a healthy mind, one that is able to anticipate future events by making generalizations from past observations (Gregory, 1980; Schacter and Addis, 2007; Snyder et al., 2004; Snyder and Barlow, 1988). Consistent with this view, as a child's mind matures; it becomes more prone to making generalizations and hence more susceptible to errors in memories for semantically related words (Brainerd and Reyna, 2007; Holliday and Weekes, 2006). Thus one might anticipate from Bartlett's (1932) observations that individuals with a more literal cognitive style would have superior "literal recall". Indeed, people with autism, who are known to be more literal (Happe and Frith, 2009), are less susceptible to errors in memories (Beversdorf et al., 2000; Hillier et al., 2007).

Interestingly, there is evidence that autistic like literal skills are associated with left hemisphere deficit together with right hemisphere compensation (Treffert, 2009). For example, Miller et al. (1998), in a classic study, showed that damage to the left anterior temporal lobe (ATL) due to dementia can lead to a more

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literal drawing style, resembling drawings produced by those with autism. There is also evidence that inhibition to the left ATL by non-invasive brain stimulation can lead to autistic like literal skills in healthy individuals in domains such as drawing (Snyder et al., 2003; Young et al., 2004), numerosity (Snyder et al., 2006), and memory (Gallate et al., 2009). This has inspired us to investigate whether memory for *visual* shapes can be temporarily improved by brain stimulation.

To achieve this goal, we used a safe, non-invasive technique, transcranial direct current stimulation (tDCS) (see Experimental procedures) that can temporarily increase or decrease excitability in a certain brain region. In particular, we adopted the identical visual stimuli (see Fig. 1a and b) as in a study by Hillier et al. (2007) which shows that people with autism are less susceptible to false recognitions and have better overall visual memory. We predict here that brain stimulation and specifically, left cathodal stimulation (decrease in excitability) together with right anodal stimulation (increase in excitability), can facilitate visual memory in healthy people. This is consistent with evidence of paradoxical facilitation (Kapur, 1996), for example, that resection to the left ATL can lead to improvement in visual memory (Baxendale et al., 2008). The logic of our stimulation protocol is based on interhemispheric rivalry (Hilgetag et al., 2001; Kinsbourne, 1977; Sack et al., 2005; Sparing et al., 2009) and is discussed further below.

2. Results

2.1. Signal detection analysis

Initially, we performed a one-way ANOVA in which the dependent variable was discrimination ability (d') and the independent variable was condition of stimulation (sham, L− R+, L+ R−). ANOVA revealed that there was no difference in discrimination ability (d') prior to stimulation across the three stimulation groups ($F(2,33)=0.29$, $p=0.75$).

We then performed a two-factorial ANOVA in which the dependent variable was discrimination ability (d') and the independent variables time (before and during stimulation) and conditions of stimulation (sham, L− R+, L+ R−). As shown in Fig. 2, ANOVA revealed a significant interaction effect ($F(2,33)=5.69$, $p=0.0075$) for conditions of stimulation. Only the "L− R+ stimulation" group showed a significant improvement ($t_{11}=3.79$, $p=0.003$, paired t-test) in visual memory (d') as a result of stimulation. There was no change in discrimination (d') performance as a result of stimulation for both the "sham stimulation" (control) group ($t_{11}=1.54$, $p=0.15$, paired t-test) and the "L+ R− stimulation" group ($t_{11}=0.50$, $p=0.63$, paired t-test). Gender is not a significant factor in explaining change (improvement) in visual memory as measured by discrimination ability (d') ($F(1,34)=0.001$, $p=0.99$).

ANOVA with the criterion scores as the dependent variable shows that conditions of stimulation did not have an effect before and during stimulation ($F(2,33)=0.36$, $p=0.70$). There was also no difference between the criterion scores before and during stimulation for the "L− R+ stimulation" group ($t_{11}=0.042$, $p=0.97$, paired t-test), the "L+ R− stimulation" group ($t_{11}=1.04$, $p=0.31$, paired t-test) or the "sham stimulation" group ($t_{11}=0.94$, $p=0.36$, paired t-test).

2.2. Errors in memories

We also performed another two-factorial ANOVA but in this case the dependent variable was the total number of mistakes ("false alarms" and "omissions in correct recognitions") participants made. As illustrated in Fig. 3, this again revealed a significant interaction effect ($F(2,33)=3.49$,

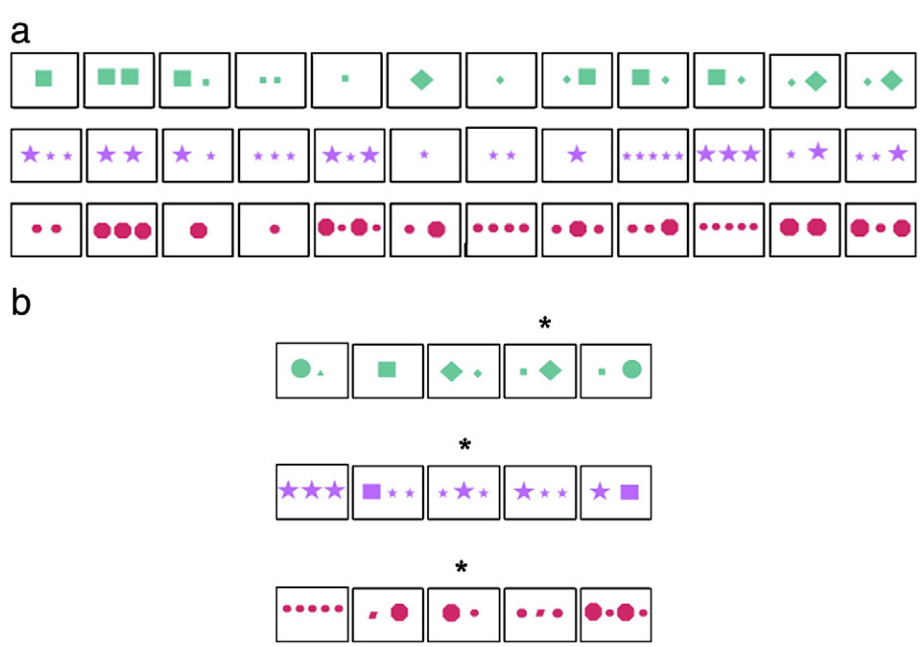

Fig. 1 – a. Examples of visual stimuli presented. Note that each row represents one set of stimuli. b. Examples of test slides as seen with each set in a where * denotes 'false alarms', slides that participants have not seen before but are related to other slides in the set.

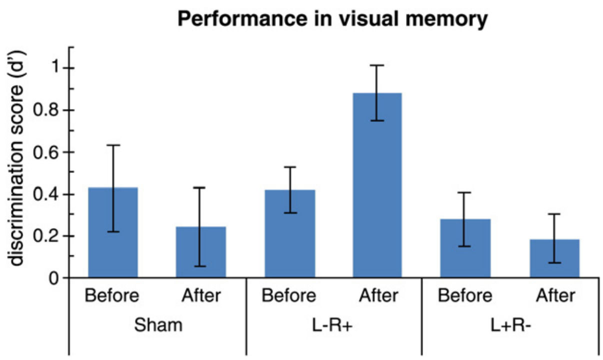

Fig. 2 – The change in visual memory (*d′*) before and during transcranial direct current stimulation (tDCS) across three stimulation conditions. ANOVA reveals a significant interaction effect ($F(2,33)=5.69$, $p=0.0075$) for conditions of stimulation. Those in the left inhibition together with right excitation group (L− R+ stimulation) showed a 110% improvement ($t_{11}=3.79$, $p=0.003$, paired *t*-test) in discrimination (*d′*) as a result of stimulation. This improvement was similar to the advantage people with high functioning autism (*d′* score of 0.78) showed over healthy individuals (*d′* score of 0.41) in the identical task in Hiller et al. (2007). The error bars represent the standard error of the mean.

$p=0.042$) and in particular, only the "L− R+ stimulation" group showed a significant reduction in the total number of mistakes ($t_{11}=3.78$, $p=0.003$, paired *t*-test) as a result of

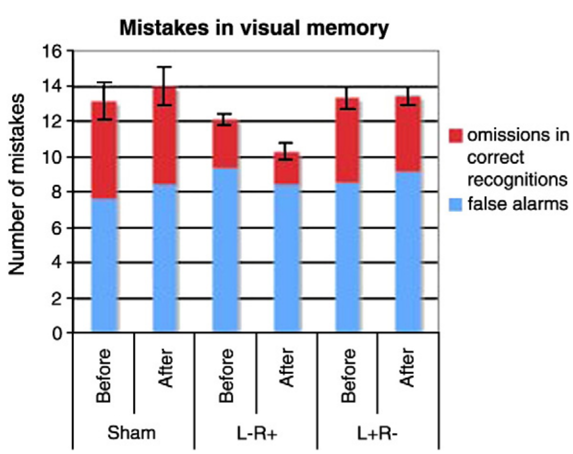

Fig. 3 – The change in the number of mistakes people make before and during transcranial direct current stimulation (tDCS). Overall, conditions of stimulation have an effect on the total number of mistakes (false alarms plus omissions in correct recognitions) participants made ($F(2,33)=3.49$, $p=0.042$). Only the left inhibition together with right excitation group (L− R+) showed a significant reduction in the total number of mistakes ($t_{11}=3.78$, $p=0.003$, two-tail paired *t*-test) as a result of stimulation. There was no change in performance as a result of stimulation for both the sham (control) stimulation group ($t_{11}=1.04$, $p=0.32$, two-tail paired *t*-test) and the left excitation together with right inhibition (L+ R− stimulation) group ($t_{11}=0.49$, $p=0.63$, two-tail paired *t*-test). The error bars represent the standard error of the mean.

stimulation. There was no change in the total number of mistakes as a result of stimulation for the "sham stimulation" (control) group ($t_{11}=1.04$, $p=0.32$, paired *t*-test) or the "L+ R− stimulation" group ($t_{11}=0.49$, $p=0.63$, paired *t*-test). More specifically, two-factorial ANOVA showed that conditions of stimulation have an effect ($F(2,33)=3.49$, $p=0.042$) on the number of false alarms, but no effect ($F(2,33)=0.32$, $p=0.73$) on the number of correct recognitions participants made. While there is no change in correct recognitions ($t_{11}=1.42$, $p=0.18$, paired *t*-test) in the "L− R+ stimulation" group as a result of stimulation, there is a trend for a significant reduction in false alarms ($t_{11}=1.89$, $p=0.085$, paired *t*-test) comparing performance before stimulation (baseline) to performance during stimulation. This finding is exploratory and will need to be confirmed in further studies with a larger sample size and power.

3. Discussion

Our result is the first demonstration that visual memory can be improved in healthy people using brain stimulation. The 110% improvement rate in discrimination ability (*d′*) as a result of cathodal stimulation (decrease in excitability) of the left ATL together with anodal stimulation (increase in excitability) of the right ATL is consistent with evidence that inhibition to the left ATL can paradoxically lead to autistic like perceptual skills in healthy people (Snyder, 2009). We believe that this is the first brain stimulation study to employ an *identical* task that had been used previously in testing autistic subjects, suggesting a possible technique for temporarily inducing an autistic like literal performance in healthy people.

3.1. *Why tDCS improved visual memories?*

We do not have a definitive explanation for the exact mechanisms leading to the improvement in visual memories. There are a number of possibilities. For example, as discussed below, the effect could be due to decrease excitability of the left temporal lobe, increase excitability of the right temporal lobe, or some combination of both.

3.1.1. *Diminishing left hemisphere dominance*

The improvement in visual memory could possibly be contributed by diminishing left hemisphere dominance as a result of cathodal stimulation of the left together with anodal stimulation of the right. This possibility is based on the classic model of interhemispheric rivalry (Hilgetag et al., 2001; Kinsbourne, 1977; Sack et al., 2005; Sparing et al., 2009). This model predicts that a) left cathodal stimulation would affect the relative hemispheric balance in the same direction as right anodal stimulation in the contralateral area (Schlaug et al., 2008; Sparing et al., 2009) and possibly that b) left cathodal stimulation together with right anodal stimulation in the contralateral area would produce an effect greater than either left cathodal stimulation or right anodal stimulation alone (Vines et al., 2008). Indeed, this explanation is supported by Christman et al. (2004) which illustrated that those who are not strongly right handed and those with bilateral saccadic eye movements (associated with weaker left hemisphere dominance and increased interhemispheric interactions) are less susceptible to errors in memories for semantically related words. It is also supported by evidence that people with high functioning autism, known to have superior visual memories (Hillier et al., 2007), are found to have atypical hemispheric dominance and are more likely to be non-right handed (Escalante-Mead et al., 2003).

3.1.2. *Reducing errors in generalizations*

By inhibiting (decreasing excitability) the left ATL, an area known to be crucial for semantic memory (Cabeza and Nyberg, 2000), context processing (Chaumon et al., 2008, 2009) and conceptual representations (Mummery et al., 2000) or labels (Gainotti, 2007), we possibly reduced the influence of context on recognition, allowing a person to be more aware of the literal details (Oliveri et al., 2004; Snyder, 2009) and less prone to errors in generalizations. This possibility is consistent with split brain studies that showed that the left hemisphere is more susceptible to errors in generalizations (Wolford et al., 2000) and false memories (Metcalfe et al., 1995). Thus from the evidence above, we reduced errors in visual memories by enhancing a more literal cognitive style and diminishing errors due to over generalizations.

3.1.3. *Facilitating the area associated with visual memory*

Another possibility is that the improvement in visual memories is mainly due to inducing greater activity in the right anterior temporal lobe, an area associated with visual memory (Bonelli et al., 2010; Dulay et al., 2009; Milner, 1968). This is also consistent with Hong et al. (2000) showing that visual working memory is lateralized in the right hemisphere and can be interfered by applying rTMS to the right inferior frontal area (F8 on the international 10–20 system) or the right inferior temporal area (T8) which is adjacent to our area of stimulation. If this were the case, the improved visual memory could be contributed by two mechanisms. One is directly due to increase in excitability (anodal stimulation) of the right anterior temporal lobe by tDCS. The other is indirectly due to disinhibition of the contralateral areas in the right anterior temporal lobe as a result of decrease in excitability (cathodal stimulation) of the left (Hilgetag et al., 2001; Kinsbourne, 1977; Sack et al., 2005; Sparing et al., 2009). This “paradoxical facilitation” is consistent with Baxendale et al. (2008) which shows that resection to the left ATL can lead to improvement in visual memory.

3.2. *Hemispheric differences*

Our finding that only participants in the “L− R+ stimulation” group had improvement shows that the improvement in visual memories is not due to practice effect or improvement in attention as neither the “L+ R− stimulation” group nor the “sham stimulation” group showed any improvement. Also, from the discussion on hemispheric rivalry above, one might have anticipated that those in the “L+ R− stimulation” group would show diminished performance in visual memories, which is not the case. A possible explanation why those in the “L+ R− stimulation” group did not perform worse is that there might be a ceiling effect in that brain stimulation cannot make someone more left hemisphere dominant than they already are. This possibility is consistent with evidence that brain stimulation can improve motor skills of people’s non-dominant hand by decreasing excitability to the dominant motor cortex but cannot improve people’s dominant hand by increasing excitability to the dominant motor cortex (Vines et al., 2008).

3.3. *Hemispheric rivalry*

The discussion above is partly based on the assumption that interhemispheric rivalry occurs at the anterior temporal lobes. This assumption is yet to be conclusively confirmed by neurophysiological evidence. However, there is extensive evidence that interhemispheric rivalry occurs with visual spatial processing in the parietal areas (Cazzoli et al., 2009; Hilgetag et al., 2001; Sack et al., 2005; Sparing et al., 2009) and in areas adjacent to the ATLs. For example, Andoh and Martinot (2008) demonstrated that TMS can induce interhemispheric compensation in Broca’s and Wernicke’s area in the temporal lobe. Even more conclusively, Thiel et al. (2006), in a PET/rTMS study, showed that trancallosal inhibition occurs at the left inferior frontal gyrus and that inhibiting this area with rTMS led to increase blood flow in the right contralateral area during a cognitive task.

3.4. *tDCS at the temporal lobes*

There are very few studies showing that tDCS can lead to cognitive enhancement. Monti et al. (2008) found that *cathodal* stimulation at the Broca’s area of the left frontemporal region led to a 33% improvement in naming accuracy. But in contrast, Floel et al. (2008) and Sparing et al. (2008) found that language learning and visual picture naming, respectively, can be improved by *anodal* stimulation at the left perisylvian area. Two studies by Boggio et al. (2009a,b) are the only ones we are aware of which show that tDCS (anodal stimulation) at the left temporal lobe can lead to enhanced memory. However, we found in our study that cathodal, not anodal, stimulation of the left temporal lobe led to improvement in visual memory. One possibility for the mixed results is that the effect of brain stimulation can be dependent on mental state (Silvanto et al., 2008), neuronal orientation in space and the type of neurons involve (Nitsche et al., 2008). In addition, tDCS effects are task dependent as shown in two similar studies aiming at the modulation of decision making (Fecteau et al., 2007a, b). Further studies should investigate enhancement of visual memory by brain stimulation in combination with neurophysiological techniques.

3.5. *Potential limitations*

3.5.1. *Limitations of our stimulation protocol*

Nevertheless, there are several limitations that need to be investigated in further studies. Firstly, since stimulation occurred during both the encoding and retrieval phase of the visual memory task, we cannot infer from our data whether encoding, retrieval or both were improved by tDCS. Furthermore, we are not able to disentangle the effect of left cathodal stimulation and right anodal stimulation in isolation to discover which has a stronger effect. This limitation may not be solved simply by including a unilateral stimulation group in the study, partly because a monopolar electrode on one hemisphere may still affect the other hemisphere through current dispersion (Lang et al., 2005). Furthermore, even if we only decreased excitability in the left temporal lobe with unilateral cathodal stimulation, it would still be difficult to exclude the possibility that any effect is mainly due to disinhibition in the contralateral area in the right hemisphere (Cazzoli et al., 2009; Hilgetag et al., 2001; Sack et al., 2005; Sparing et al., 2009). A bilateral stimulation design with opposite polarities is the most efficient design for testing the possibility that tDCS can lead to improvement in visual memory in healthy people. It also presumably ensures that, the level of sensation between the two active conditions was indistinguishable and that current dispersion was minimal. However, since we found a strong improvement in visual memory, in future investigations it might be worthwhile to explore other methods of stimulation such as unilateral stimulation (but with a large electrode in the contralateral hemisphere as to have a functional unilateral stimulation), in combination with neuroimaging techniques, to investigate specific questions about the mechanisms of actions leading to the improvement.

3.5.2. Limitation in neuroanatomical specificity

Another limitation is that the effect of tDCS is not particularly focal (Nitsche et al., 2008) and thus it is difficult to make definitive conclusions in regard to neuroanatomical functions. The sponge electrodes is 5×7 cm and thus it is possible that areas adjacent to the anterior temporal lobe such as the inferior frontal lobes (F7 or F8) were stimulated. Even if tDCS was more focal, it would be difficult to determine if any cognitive improvement was due to local or distant network effects (Nitsche et al., 2008). Nevertheless, there is growing evidence that the behavioral effects of tDCS are relatively focal and are associated with excitability change. For example, both Fregni et al. (2005) and Marshall et al. (2004) showed that memory can be improved by increasing excitability in the frontal areas with tDCS. There is also evidence that increasing excitability by tDCS in the parietal areas (Sparing et al., 2009) and the posterior perisylvian region (Floel et al., 2008) can lead to improvement in cognition. Furthermore, based on the evidence from dementia studies (Miller et al., 1998) and rTMS (more focal than tDCS (Sparing and Mottaghy, 2008)) studies showing that inhibition to the left ATL can lead to autistic like literal skills (Snyder, 2009), we believe that the mechanism leading to the improved visual memory discrimination is most likely due to modulation of excitability in the anterior temporal lobes. However, this will need to be confirmed by further studies with neuroimaging and EEG.

3.6. General conclusion

We found that cathodal stimulation of the left anterior temporal lobe together with anodal stimulation of the right anterior temporal lobe led to a pronounced improvement in visual memory. Our findings are consistent with Bartlett's observations that memories are not literal representations of the past, so that those with a more literal cognitive style, like those with autism or an inhibited left ATL, should be less prone to errors.

4. Experimental procedures

4.1. Study participants

We included healthy right handed participants aged between 18 and 40 years (mean age of 23). Handedness was assessed by the Edinburgh Handedness Inventory and only participants with a score of more than 50 were recruited in this study. Participants were screened and excluded if they had any neuropsychiatric disorder, current or past history of drug use, were taking any medication acting on the central nervous system or were pregnant. Thirty six participants (23 females) were enrolled in this study and twelve participants were randomly assigned to each of the three treatment conditions. Participants gave written informed consent for the study. The study was carried out to conform to the principles of the Declaration of Helsinki and was approved by the University of Sydney ethics committee.

4.2. Transcranial direct current stimulation (tDCS)

tDCS is based on the application of a weak direct current to the scalp via two saline-soaked surface sponge electrodes. It is an attractive tool for our goal of improving visual memory because it is a non-invasive and safe method of modulating membrane resting threshold and thus temporarily increasing or decreasing neuronal firing activities (Iyer et al., 2005; Nitsche and Paulus, 2000). Nitsche et al. (2006) have shown that tDCS induces significant changes in excitability during stimulation and that these changes are similar in magnitude to the after-effects of tDCS.

Direct current was transferred by a saline-soaked pair of surface sponge electrodes (35 cm^2) and delivered by a battery-driven (three 9-V batteries), constant current stimulator with a maximum output of 2 mA. The tDCS device was specially developed and customized with the specification as described in the text. The current was manually and slowly (30 s) ramped up and down. The device has a safety built-in system that prevents currents higher than 2 mA. Stimulation was applied for approximately 13 min (according to the duration of the task—stimulation was ended when the visual memory task was completed). This stimulation intensity is weaker than the intensity shown to be safe by Iyer et al. (2005).

Participants were randomized to receive one of three different types of treatment:

1) Cathodal stimulation of the left anterior temporal lobe and anodal stimulation of the right anterior temporal lobe (referred in the text as "L− R+ stimulation"). In the text, the symbol "+" refers to the property of increase in excitability (anodal stimulation); the symbol "−" refers to the property of decrease in excitability (cathodal stimulation). The cathode electrode was placed over at the left ATL, approximately half way between T7 and FT7 on the International 10–20 System for electrode placement. The anodal electrode was placed over at

the right ATL, approximately half way between T8 and FT8 on the same 10–20 System. The area is laterally 40% of the intra-auricular distance from the vertex and anteriorly 5% of the distance from inion to nasion. The areas were determined with the guidance of an EEG cap.

2) Anodal stimulation of the left anterior temporal lobe and cathodal stimulation of the right anterior temporal lobe (referred in the text as "L+ R− stimulation"). The anode electrode was placed approximately half way between T7 and FT7 on the International 10–20 System and the cathode electrode approximately half way between T8 and FT8 on the same 10–20 System.

3) Sham stimulation. For sham stimulation, the electrodes were placed in the same positions as in active stimulation (L− R+ stimulation); however, the stimulator was turned off after 30 s of stimulation. Therefore, participants felt the initial tingling sensation associated with turning on the device, but received no current stimulation for the rest of the treatment period. Importantly, it is not possible for the subject to guess current direction (anodal and cathodal stimulation induce similar sensations). It has been shown that this method of sham stimulation can blind subjects in a reliable way (Gandiga et al., 2006).

4.3. *Experimental stimuli*

We used the identical visual stimuli as used in a recent study (Hillier et al., 2007) which shows that autistic people have better visual memory than that of neurotypicals. This task corresponds to the visual analog of Roediger and McDermott's, 1995 classic paradigm for investigating false memories (see Fig. 1a and b). Each set of stimuli depicted a different type of shape including squares, crosses, circles, triangles and so on which varied in number, arrangement, color and size on each slide (see Fig. 1a). During the study phase, participants were presented with 12 slides related by a common theme appearing one by one on the screen. Immediately after that, participants were presented with an additional five test slides, and were tested for recognition. Of the five test slides, two had been presented previously ("correct recognitions"), two clearly had not, and one was a "false alarm" slide, which was strongly related to the slides in the set but was not presented (see Fig. 1b). Participants were asked to report whether they have seen the slide before following the same procedure as in the study by Hiller et al. (2007).

Hillier et al. (2007) used 24 sets of slides in their experiment. Each set containing 12 study slides and 5 test slides. In our study, we divided the 24 sets into odd and even versions and counterbalanced the two versions before stimulation (baseline) and during stimulation. The slides were presented on a computer screen using Microsoft PowerPoint. The size of the slide is 13″ × 9.5″ and each slide was shown for 2 s at a viewing distance of around 30″.

4.4. *Procedure*

Subjects were first asked to complete one version of the visual memory task (each version of the task consists of both the study and testing phase as seen, for example, in Fig. 1a and b). This is prior to stimulation in order to establish baseline performance. Subsequently, subjects received one of the three stimulation conditions (sham, L− R+ or L+ R−) for 5 min and then they were asked to complete the other version of the visual memory task while the stimulation continued. The rationale here was that cortical excitability changes induced by tDCS are usually observed after a period of 3–5 min (Nitsche and Paulus, 2000). We continued stimulation until the end of the cognitive task to ensure that there is sufficient change in cortical excitability during the task. Since it takes approximately 8 min to complete the visual memory task, the total duration of stimulation is approximately 13 min.

4.5. *Signal detection analysis*

We were interested in finding out whether tDCS can improve visual memory. For example, the ability to discriminate slides seen previously (correct recognitions) from slides not seen previously (false alarms). We assess this discrimination ability using the sensitivity index (d') from signal detection theory, which was also the measure used to assess visual memory in Hillier et al. (2007). This is an ideal measure because the sensitivity index (d') takes into consideration both the number of false alarms and the number of correct recognitions. This measure quantifies the ability to detect signal from noise and is calculated by the z-transform of the correct recognitions minus the z-transform of the false alarms. The z-transformation standardizes (normalizes) the values so that it has a mean of zero and a variance of one. In our calculation, correct recognitions (slides that participants have actually seen before) were considered as signal; false alarms (slides that participants have not seen before but *are* related to the slides in the set) were considered as noise. Our pilot study showed that hardly any participant made mistakes on slides that they have not seen before and were *not* similar to the slides in the set. Thus these data were not analyzed because there might be a ceiling effect. We also analyzed the criterion scores which can be interpreted as an indication as to how conservative participants are in saying 'yes' that they have seen the item previously.

4.6. *Statistical analysis*

We initially performed a one-way ANOVA in which the dependent variable was discrimination ability (d') and the independent variable was the condition of stimulation (sham, L− R+, L+ R−). The threshold for significance is set to be $p<0.05$. We also performed a two-factorial ANOVA in which the dependent variable was discrimination ability (d') and the independent variables time (before and during stimulation) and conditions of stimulation (sham, L− R+, L+ R−). Post-hoc comparisons using two-tailed Student's t-tests were then performed if appropriate. Because we had three treatment groups and therefore three possible pairs of comparisons, we adjusted the threshold for significance using Holm's procedure (Aickin and Gensler, 1996) to avoid an inflated Type 1 error rate. This procedure of adjustment is shown to be more powerful than Bonferroni's procedure (Aickin and Gensler, 1996). In our multiple comparisons, the adjusted alpha for the Student's t-test is set to be $p=0.0167$ for the most significant pair and $p=0.025$ for the second most significant pair. Finally, we also added gender in the ANOVA model to assess whether there is a gender effect in our results.

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