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Research report

Combination of a short cognitive training and tDCS to enhance visuospatial skills: A comparison between online and offline neuromodulation

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ABSTRACT

Visuospatial skills can be enhanced thanks to specific intervention programs, but the additional benefits of neuromodulation on these skills have not been fully investigated yet, although transcranial direct current stimulation (tDCS) has demonstrated to boost the effects of cognitive trainings. When combining cognitive intervention with neuromodulation, the time-window of tDCS application in relation to task execution has to be taken into account since it has been shown to affect stimulation outcomes. The aim of the present experiment was to investigate the influence of tDCS in enhancing the effects of a training for visuospatial skills. We hypothesized that tDCS applied during training execution (online) would improve the cognitive performance at a larger extent than tDCS applied before training execution (offline). Participants received anodal tDCS over the dorsolateral prefrontal cortex during (online) or before (offline) the completion of the training. A control sham condition was included. Visuospatial abilities were measured 24 h before (day 1, pre-test) and 24 h after (day 3, post-test) the stimulation and training session (day 2). tDCS enhanced gains for mental folding performance when applied during the execution of the training (online). Participants' mental rotation and mental folding performance improved from pre-test to post-test regardless of the stimulation condition. However participants in the online tDCS condition showed the largest improvement in mental folding performance. Findings indicate that tDCS enhanced the effects of the training when applied during its execution, showing cumulative positive aftereffects on visuospatial performance 24 h after the stimulation session. The time-dependent effect points out the importance of the time-window of tDCS application in influencing behavior when combined with cognitive programs.

1. Introduction

An increasing number of training programs focusing on cognitive skills combine behavioral protocols with non-invasive transcranial electrical stimulation (tES) techniques to enhance the effects of the intervention (Au et al., 2016; Talsma et al., 2016; Ditye et al., 2012; Martin et al., 2013; Ownby and Acevedo, 2016; Andrews et al., 2011; Elmasry et al., 2015). tES is supposed to amplify the outcomes of intervention programs thereby the modulation of the neural activity elicited by the training (Miniussi and Vallar, 2011). To be more specific, it is conjectured that tES enhances the synaptic strengths of neurons within the cortical networks that are specifically activated by the training. Boosting the endogenous neuronal activation underlying cognitive processes engaged in a training-task by means of neuromodulation is suggested to produce cumulative improvement effects (Meinzer et al., 2012).

Among tES, transcranial direct current stimulation (tDCS) is a brain modulation technique that applies a continuous, low intensity electrical direct current on the scalp. This has been proved to alter cortical excitability by either hyper- or hypo-polarizing the neuronal membrane potential according to the polarity of the stimulation (Nitsche and Paulus, 2000). Training programs combined with tDCS have shown stimulation-enhanced improvements on working memory (Martin et al., 2013; Richmond et al., 2014), problem solving (Iannello et al., 2014), cognitive control (Segrave et al., 2014), planning ability (Dockery et al., 2009), and learning

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(Ambrus et al., 2011) in healthy participants, pointing to tDCS as a promising tool for increasing the effectiveness of the proposed exercises.

Nevertheless, a consensus is developing that the heterogeneity of tDCS outcomes found in the literature depends on the application of different stimulation setups (Tremblay et al., 2014; Dedoncker et al., 2016). Specifically, the time-window in which tDCS is administered in relation to task execution has been identified as a factor influencing the impact of the stimulation on behavior (Dedoncker et al., 2016). For example, tDCS was demonstrated to cause different effects depending on the timing of the application of stimulation, as shown by faster motor learning during tDCS vs. slower learning when tDCS was administered prior to the performance (Stagg et al., 2011). A recent study (Pirulli et al., 2013) reported opposite results regarding improvement in perceptual learning, which occurred only when tDCS was applied before the task, but not when it was applied during the execution of the task. Moreover, Ohn and colleagues (Ohn et al., 2008) found enhanced working memory performance after 10 min of tDCS application. This effect was further enhanced 30 min after the end of the stimulation. Time-dependent effects of stimulation protocols emerged also in studies combining neuromodulation protocols with cognitive training, reporting better training skill acquisition during tDCS (online effects) as compared to training skill acquisition measured following the stimulation session (offline effects) (Andrews et al., 2011; Martin et al., 2014). It follows that understanding the optimal timing for the administration of tDCS is crucial to design effective combined tES and training interventions.

To our knowledge, tDCS has never been combined to training interventions aimed at enhancing visuospatial skills. Cognitive training based on continuative practice exercises showed to improve visuospatial performance (Debarnot et al., 2013; Jaušovec and Jaušovec, 2012; David, 2012; Boakes, 2009) and neuromodulation could potentially enhance this effect. Moreover, empirical evidence supported the notion that practice not only improves performance in trained visuospatial tasks, but that this effect can also be transferred to similar non-trained abilities (Wright et al., 2008). Visuospatial abilities, like mental rotation and mental folding, are thought to consist of a series of subprocesses that include the encoding of the stimulus, the maintenance of the information in a short-term storage system, and the transformation (rotation/translation) of the stimulus according to temporary task's demand in face of distractors (Miyake et al., 2000). Components as maintenance of relevant information, scheduling and coordination of sequence of mental transformations, inhibition of distractors, and management of attentional resources according to task's goals and sub-goals together point to the supportive role of executive control component to visuospatial processing (Shah et al., 2005; Kane and Engle, 2002). The idea of a contribution of executive control mechanisms to visuospatial processes finds empirical evidence in a study by Miyake and colleagues (Miyake et al., 2001), who examined the correlations between executive functions and factors underlying spatial abilities. The authors found strong correlations between executive function measures and the factor identified as "spatial visualization", which includes the encoding and the mental manipulation of the spatial properties of an object (Carroll, 1993). Conversely, the factor "perceptual speed", defined as the rapidity in the comparison of stimuli based on their visual characteristics (French, 1953), was associated to executive functions to a lesser degree (Miyake et al., 2001).

When planning a tDCS-based training, choosing the target brain areas obviously plays a major role. In this case the dorsolateral prefrontal cortex (DLPFC) appears to be a good candidate. Neuroimaging research has shed light on the role played by the DLPFC in multiple executive components as monitoring of representations held in the working memory system (D'Esposito et al., 1998) and inhibition of distractors (Postle et al., 1999). The involvement of the prefrontal cortex in executive controls across modalities (Spagna et al., 2015) is in agreement with empirical evidence reporting the activation of prefrontal regions during the execution of different modality-specific tasks, including visuospatial tasks (Zacks, 2008). Along with the well-established link between the elaboration of spatial features and the activation of the superior parietal cortex and adjacent areas (Lamp et al., 2016), activity of the DLPFC cortex during visuospatial processing has been observed in several studies (Cohen et al., 1996; Kosslyn et al., 1998; Kosslyn et al., 2001; Owen et al., 1996). The activation of this brain region during mental rotation has been hypothesized to be linked to the monitoring in the working memory system of the spatial location of the parts of the to-be-transformed stimuli (Cohen et al., 1996). The contribution of the DLPFC to short-term storage of spatial information is also supported by findings from lesion studies, which showed patients with prefrontal cortex damages to perform poorly in mental rotation tasks (Oliveri et al., 2012; Incorpora et al., 2010; Buiatti et al., 2011). Moreover, tDCS-induced changes in spatial working memory tests have been observed following stimulation of the DLPFC (Alencastro et al., 2016; Giglia et al., 2014).

The general aim of the present study was to investigate the effects of an ad-hoc training for visuospatial abilities combined with the administration of tDCS over the DLPFC. In light of the encouraging results of previous research showing tDCS ability to boost the improvements elicited by cognitive trainings and given the importance of the timing of the stimulation in modulating behavior (Wu et al., 2014), the scope of our experiment was twofold. Our primary interest was to investigate whether the tDCS-induced changes in cortical excitability would modulate the improvement determined by the training, boosting its effect. Secondly, we were interested in exploring possible time-dependent effects of the stimulation. In order to address this issue, tDCS was applied either during or immediately before the execution of the training. We hypothesized that online tDCS would prove effective in enhancing the training improvements as compared to offline tDCS, in line with previous research (Stagg et al., 2011; Martin et al., 2014). Given the established gender differences in visuospatial abilities (Halpern, 1992), potential differences between men and women in visuospatial performance and its interaction with the stimulation were also explored.

2. Results

IBM SPSS Statistics 20.0 was used for all statistical analyses. Two separate one-way ANOVAs were computed to detect possible differences in baseline performance at the Shepard and Metzler mental rotation task (S&M) and the Paper Folding & Cutting task (PF&C) among conditions. Analyses revealed that at baseline both S&M and PF&C mean accuracy scores were comparable between the groups (S&M, $F_{2,26} = 0.13$, $p = 0.88$, $\eta^2_p = 0.01$; PF&C, $F_{2,14.84} = 0.74$, $p = 0.49$[1], $\eta^2_p = 0.07$) (Table 1). In order to test whether tDCS influenced participants' ability to undertake the visuospatial training, a one-way ANOVA on training percentage accuracy, calculated by dividing the number of exercises solved correctly by the number of total items, was computed. Results did not show any significant difference on training percentage accuracy among conditions ($F_{2,26} = 1.19$ $p = 0.32$) (Table 2).

ANOVAs on post-test mean accuracy were carried out to test cumulative effects of stimulation and training on non-trained visuospatial abilities on day 3. No significant difference emerged from analyses on mean accuracy of both S&M and PF&C tasks according

[1] Welch Test results.

Table 1
Mean accuracy and SD of S&M and PF&C tasks per time (pre/post-test) and among groups.

	Pre-test				Post-test			
	S&M		PF&C		S&M		PF&C	
	M	SD	*M*	SD	*M*	SD	*M*	SD
online tDCS	10.85	3.42	11.15	2.95	11.90	2.23	13.05	2.47
offline tDCS	11.44	2.53	12.28	1.70	13.33	1.52	13.06	1.99
sham	11.44	2.58	12.69	2.60	11.94	2.70	12.88	2.68

Table 2
Means and SDs of training percentage accuracy and RTs among groups.

	% accuracy		RTs	
	M	SD	*M*	SD
online tDCS	61.18	22.22	16.80	3.46
offline tDCS	47.06	19.29	14.78	3.03
sham	58.09	20.24	15.13	3.98

to the stimulation condition (S&M, $F_{2,26} = 1.26$, $p = 0.30$, $\eta_p^2 = 0.10$; PF&C, $F_{2,26} = 0.05$, $p = 0.98$, $\eta_p^2 = 0.01$). Additionally, we performed two ANOVAs on gain scores, computed for each participant by subtracting pre-test scores from post-test scores for both S&M and PF&C tasks. The question of interest we tried to address here was whether the improvement observed from pre-test to post-test was influenced by tDCS according to stimulation timing (i.e., online vs. offline stimulation) as compared to sham tDCS. The first analysis on the mean gain score of S&M task did not show any significant difference among groups ($F_{2,26} = 1.70$, $p = 0.20$, $\eta_p^2 = 0.12$). A significant main effect of stimulation condition emerged in the second analysis performed on the mean gain scores of PF&C task ($F_{2,26} = 5.19$, $p = 0.01$, $\eta_p^2 = 0.30$). Bonferroni-corrected pair-wise comparisons revealed a significant difference between online and sham tDCS (mean difference = 1.71, SE = 0.55, $p = 0.01$), but not between online and offline tDCS (mean difference = 1.12, SE = 0.53, $p = 0.13$), nor between offline tDCS and sham condition (mean difference = −0.59, SE = 0.56, $p = 0.91$)[2] (Fig. 1). A mixed ANOVA on PF&C task's mean accuracy confirmed the latter result, showing a significant interaction effect between time and stimulation condition ($F_{2,24} = 5.19$, $p = 0.01$, $\eta^2 = 0.30$) (Fig. 2). Paired-sample *t*-test comparisons computed for each stimulation group separately indicated a significant improvement in performance in the online tDCS group ($t_9 = 4.39$, $p = 0.002$), whereas the improvement observed in the offline tDCS ($t_8 = 1.99$, $p = 0.08$) and sham condition ($t_7 = 0.70$, $p = 0.50$) did not reach statistical significance. The time X condition interaction effect that emerged from the general linear model applied to S&M mean accuracy was not significant ($F_{2,24} = 0.27$, $p = 0.77$). Lastly, in light of previous research that has demonstrated that men have an advantage for mental rotation performance in comparison with women (Halpern, 1992; Voyer et al., 1995), we were also interested in observing possible gender differences in visuospatial abilities in the present study. Independent-sample *t* test analyses on baseline visuospatial measures (S&M: $t_{25} = 0.05$, $p = 0.82$; PF&C: $t_{25} = 0.43$, $p = 0.52$), performance during the training ($t_{24,67} = 1.62$, $p = 0.12$) and gain scores (S&M: $t_{25} = 0.23$, $p = 0.69$; PF&C: $t_{25} = 0.72$, $p = 0.41$) failed to support gender differences.

[2] Least significant difference (LSD) post hoc comparisons showed a significant difference between online and sham tDCS (mean difference = 1.71, SE = 0.55, p = 0.005), between online and offline tDCS (mean difference = 1.12, SE = 0.53, p = 0.05), but not between offline tDCS and sham condition (mean difference = −0.59, SE = 0.56, p = 0.30).

3. Discussion

The main scope of the present study was to examine tDCS-induced cortical changes in boosting the effect of a cognitive training. Anodal tDCS over the dorsolateral prefrontal cortex was administered during (online) or immediately before (offline) the completion of an ad-hoc training aimed at increasing visuospatial skills. Dependent variables were mental rotation and metal folding skills, assessed by means of the Shepard and Metzler (S&M) paradigm and the Paper Folding & Cutting (PF&C) task respectively, measured 24 h before (*day 1*, pre-test) and 24 h after (*day 3*, post-test) the stimulation session (*day 2*).

Analyses revealed tDCS time-dependent and task-dependent effects, as tDCS enhanced gains for the PF&C performance when applied during the training. Participants' performance both at S&M and PF&C tasks improved from pre-test to post-test regardless of the stimulation condition. However participants in the online tDCS condition showed a large improvement at the PF&C performance 24 h after the stimulation session as compared to participants in the offline tDCS and sham condition. Online tDCS did not facilitate immediate accuracy in performing the training on *day 2*, but positive aftereffects were observed at post-test the following day. These findings are in line with previous works that demonstrated online tDCS to enhance the outcomes of trainings if compared to offline tDCS (Reis et al., 2015) and sham control condition (Martin et al., 2014) on the day following the stimulation session, presumably thereby strengthening online skill acquisition during practice. It has been hypothesized that the offline gains are increased by the process of consolidation of skills and/or strategy through practice, resulting from the specific interaction between the endogenous neural activation elicited by the training and the simultaneous, exogenous electrical stimulation (Miniussi and Vallar, 2011).

Even though both S&M and PF&C tasks require to manipulate mental images, the task-specificity emerged in this experiment arises the question, already discussed in the literature (Atit et al., 2013; Harris et al., 2013), whether mental rotation and mental folding share the same cognitive processes and neural mechanisms. To be more precise, both operations focus on transforming internally specified representations of objects and the tasks used to assess these operations are usually performed on the basis of spatial processes, but are susceptible to non-spatial strategies as well. Yet, these operations differ in two ways. Mental rotation is a transformation that does not change the shape and the size of the manipulated object. By contrast, mental folding affects the given stimulus by transforming it into something different. Moreover, mental rotation is associated to gender differences, whereas mental folding does not (Harris et al., 2013). On a cognitive level, a mental folding task usually requires participants to imagine to refold or unfold an image following a coordinated sequence of transformations. Conversely, a mental rotation task can be performed by a single, holistic mental rotation. Owing to the presence of multiple transformation that can be carried out on individual parts of the image separately, it has been argued that mental folding is more amenable to be carried out by a verbal-analytic rather

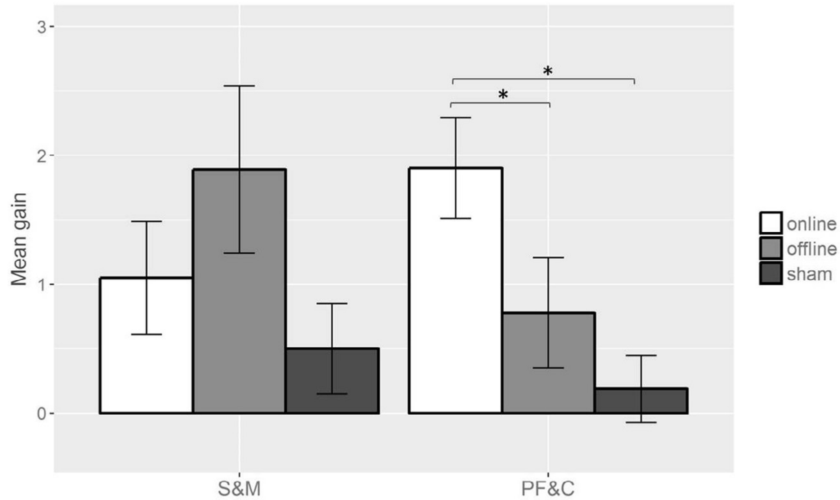

Fig. 1. Main gain score of S&M and PF&C tasks among groups. Bars represent ±SEM.

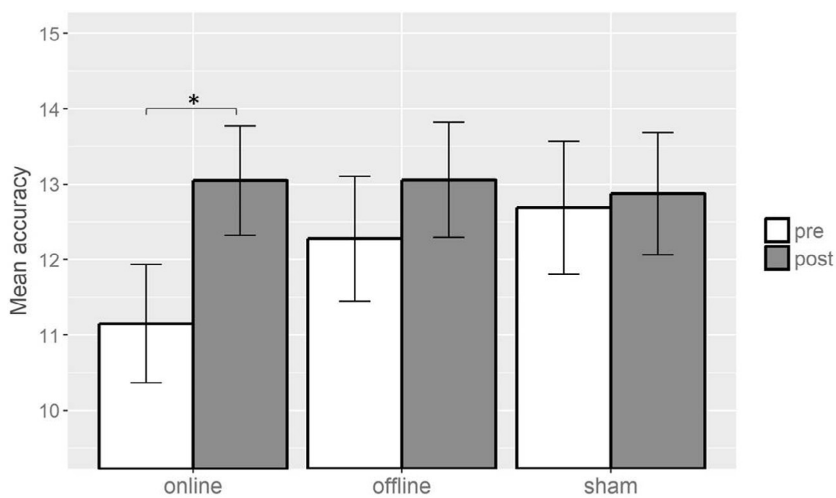

Fig. 2. Pre and post-test mean accuracy of PF&C task among groups. Bars represent ±SEM.

than a spatial approach as compared to mental rotation (Lohman, 1979). This explanation is supported also by results of studies on the neurological bases of these processes. Results from this line of research showed that both processes are linked to the activation of the parietal lobe and adjacent areas (Zacks, 2008). Several neuroimaging studies have pointed out the superiority of the right hemisphere in visuospatial processing, but bilateral and left activation has also been reported (Zacks, 2008). However, results of an EEG study confirmed the presence of a strong right hemisphere lateralization for mental rotation, whereas parietal event-related potentials registered during mental folding showed no significant lateralization (Milivojevic et al., 2003). The authors have proposed that the bilateral cortical activity observed during mental folding may be due to the specific nature of the task. As mentioned above, compared to the, holistic transformations performed in mental rotation, mental folding requires a series of coordinated local piece-wise operations (Harris et al., 2013). According to the assumption that the more the hierarchical operations are executed, the less parallel is the process (McGuiness and Bartell, 1982), the continuum of operation complexity may account for the degree of lateralization observed during different type of visuospatial processing. Moreover, the coordination of a sequence of mental transformations characterizing mental folding seems to reflect operations, as planning and control of cognitive resources in presence of high task demands, associated with the activation of the left DLPFC (Kaller et al., 2011; Koechlin et al., 2003; Yoshida et al., 2010). Therefore, it can be speculated that the observed task-dependency is due to the specific stimulation setup, targeting the left DLPFC, which may have influenced, among the different sub-mechanisms involved in visuospatial processing, the ability to coordinate a sequence of mental transformations through the top-down interactions existing between this region and posterior associative cortices.

In accordance with this possible explanation, besides the heterogeneity of the effects of different stimulation parameters (To et al., 2016), growing attention has been directed to the potential role of task characteristics in modulating tDCS effects (Bikson et al., 2013). Gill and colleagues (Gill et al., 2015) pointed out that the outcomes of stimulation are influenced by the nature of the cognitive activity elicited by the task applied. This claim is supported by their findings that showed improved high-level difficulty in n-back task performance during anodal stimulation over the DLPFC, whereas the same stimulation protocol did not lead to any changes in performance when participants faced a low-level difficulty version of the same task. Given that tDCS does not directly stimulate action potential in neurons, whereas it modulates their spontaneous firing frequency, the authors argued that the extent to which tDCS is able to affect cortical excitability depends on the state of activation of the neural networks, which are, in their turn, activated accordingly to specific cognitive loads and demands. Thus, in the present study both the level of operation complexity of mental folding and the specific tDCS montage applied, targeting the left DLPFC, together may explain why we found tDCS-induced offline gains only for PF&C performance.

Our results go along with previous findings that showed anodal tDCS to enhance the effects of cognitive trainings, reporting cumulative positive aftereffects 24 h after the end of the stimulation session (Martin et al., 2014; Reis et al., 2015). We propose that the task-specific effect may have resulted from the interaction between the level of operation complexity of the task, which was higher for the PF&C task than for the S&M task, and the specific tDCS protocol applied. The time-dependent effect that emerged here seems to point to the time-window of application as a crucial factor able to influence the outcomes of the stimulation when combined with a cognitive program, as highlighted in previous research (Andrews et al., 2011; Martin et al., 2014; Reis et al., 2015).

Nevertheless, this study suffers from several limitations. Firstly, besides a modest sample size, the between-subjects design adopted did not allow us to control for inter-subject variability relative to the stimulation (Horvath et al., 2014). On the other hand, using a within-subject design, thus presenting the same set of stimuli multiple times, could have led participant to further familiarize with the task, making difficult to distinguish between an actual improvement in visuospatial processing from a change in the process of information retrieval, which has been suggested to account for better accuracy following continuative practice (Heil et al., 1998). Secondly, we did not observe whether participants used a holistic or a verbal strategy to solve the tasks. Therefore we cannot exclude that our results were influenced by strategy-dependent components in task preparation and by their interaction with the stimulation. Lastly, the relatively high number of correct responses in both tasks might be read as a hint of a ceiling effect.

Future research may address these limitations by way of using different tasks and control for participants' actual strategies while solving the rotation task. Planning a TMS-based study could also provide further evidence for our conclusions, given the higher level of precision of the stimulation. TMS would allow researchers stimulating specific subareas of the DLPFC, potentially differentiating among mental rotation tasks, allowing a better understanding of the effects of brain stimulation on specific spatial abilities.

4. Experimental procedure

4.1. Design

The present study adopted a single-blind, one-factor design, with the stimulation condition (anodal online vs. anodal offline vs. sham tDCS) as the independent between-subjects factor.

4.2. Participants

Twenty-eight healthy adults volunteered in the study. One participant was excluded owing to low accuracy at the tasks (scores lower than 2 standard deviations above or under the mean were defined as outliers and discarded). This yielded to a final sample of 27 participants (18 women; $M = 26.5$ yrs., $SD = 6.3$). Gender, age, and handedness were homogeneously distributed across conditions (gender: $\chi^2_{2,27} = 0.11$; $p = 0.90$ – age: $F_{2,24} = 2.22$, $p = 0.13$ – handedness: $\chi^2{}_{2,27} = 4.32$; $p = 0.12$).

Prior to the experiment participants filled in a questionnaire to evaluate their suitability for tDCS. None of the volunteers had a history of neurological disorders, brain trauma, or a family history of epilepsy. Written informed consent was obtained from all participants prior to the experiment. The study was carried out according to a protocol approved by the local ethics committee and in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

4.3. Materials

4.3.1. Shepard–Metzler mental rotation task and paper folding & cutting task

To assess mental rotation ability, a modified version of the Shepard and Metzler (S&M) paradigm and the Paper Folding & Cutting (PF&C) subtest of the Stanford-Binet test were administered in a digital form (Shepard and Metzler, 1988; Thorndike et al., 1986). These tasks were selected among those that address the mental rotation ability in a way that mirrored the tasks of the training as closely as possible. They also assess specific skills linked to kinds of mental rotation that, according to the literature, can be trained and lead to durable training effects (Harris et al., 2013). Moreover, these tests, apart from being widely used as yet (Lamp et al., 2016; Gardony et al., 2017; Sladky et al., 2016), have also been applied in research projects that shared some similarities with our study (Jaušovec and Jaušovec, 2012; Jaušovec, 2012; Pahor and Jaušovec, 2014).

The S&M was a same-different comparison task consisting of 30 pairs of three-dimensional cube stimuli in which one figure was rotated with respect to the other one. Participants were asked to indicate whether the figures were identical (i.e., the same figure only rotated) or if two different stimuli were displayed instead.

The PF&C task was composed of 30 items, each one presenting a figure in the left frame, which represented how a piece of paper was folded and cut, along with four other figures showing different unfolded and cut papers on the right frame. Participants were asked to indicate which one of the four provided alternatives corresponded to the folded paper displayed in the left frame.

Both tasks were presented on a desktop computer screen using $STIM^2$ software, in counterbalanced order across subjects. In each of the 60 items participants were exposed to the figure and were instructed to respond, as quickly as possible, using the keyboard. When facing the S&M task, participants provided their response by pressing the letter "z" when the figures were judged to be the same figure yet rotated or "x" when the figures were judged to be two different objects. Regarding the PF&C task, participants responded by pressing the letters "z", "x", "c" or "v", each one corresponding to one the four alternatives displayed. Response times were registered in milliseconds for each item of the two tasks. An interval of 2 s separated the items after the participant gave his/her response.

4.3.2. Transcranial direct current stimulation (tDCS)

A continuous low direct current stimulation of 1.5 mA was induced by two surface sponge electrodes covered in conductive gel (25 cm^2; current density: 0.06 mA/cm^2) and delivered by a battery-driven, constant-current stimulator (HDC Series by Newronika S.r.l, Milan) for 20 min with a ramp-up time of 30 s. In the unilateral anodal condition, for both online and offline condition, the active anode electrode was positioned over the left DLPFC, whereas the reference cathode electrode was placed over the right deltoid muscle. This montage has been proved effective in modulating physiological and behavioral performance in similar studies (Colombo et al., 2015; Filmer et al., 2014; Im et al., 2012; Nasseri et al., 2015; Oldrati et al., 2016). In the sham condition, electrodes were positioned as in the unilateral anodal condition, but the

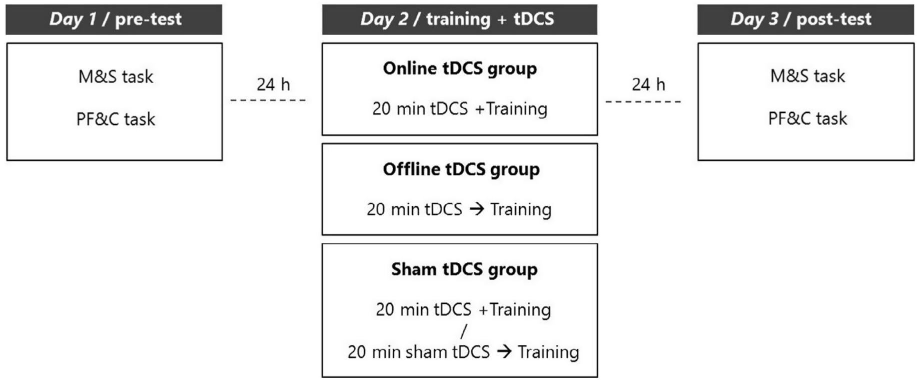

Fig. 3. Phases of the testing procedure.

current was automatically turned off after 10 s from the beginning of the stimulation. To ramp off stimulation allows participants to feel the characteristic tingling sensations in the vicinity of the electrodes and, therefore, makes possible to keep them blind to the stimulation condition. The DLPFC was localized using the international 10–20 system (EEG) and F3 was identified as the target area (Cerruti and Schlaug, 2009).

4.3.3. Visuospatial skill training

A paper-and-pencil training for visuospatial abilities was created ad hoc for the study. It consisted of 4 types of visuospatial tasks for a total of 17 exercises: a mental rotation task of two-dimensional objects, a paper-folding task of three-dimensional objects, a cube comparison, and a spatial perspective-taking task (fig. supplementary).

Items of the *mental rotation task* consisted in 3 × 3 or 4 × 4 matrices, each one with either three or four color printed cells respectively. Participants were asked to mentally rotate the matrices twice, left or right and up or down, according to the instructions. Lastly, they were required to draw how the matrices would appear after the mental rotation. The *paper-folding task* consisted of two sub-tasks. In the first one, participants were asked to mentally unfold a target cube with different shapes printed on each of one of the three visible faces. Then they had to select, among four alternatives, the template that correctly represented the target cube once unfolded, considering the spatial arrangement of the shapes printed on the sides. In the second sub-task participants were asked to mentally fold up an unfolded a cube with two arrows printed on two of its six faces and, once the required mental operation was concluded, to indicate on a folded cube the position of the arrows. In the *cube comparison task* each item presented two cubes, once again with different shapes printed on their sides. Participants were required to indicate whether the two drawings could show the same cube. Lastly, the *spatial perspective-taking task* was composed of two types of exercise. In the first one participants were presented with pictures of complex structures made of three-dimensional geometric solids. Within this three-dimensional environment, a picture of a man was included. Participants were asked to imagine the spatial arrangement of the geometric solids taking the perspective of the man and to choose the correct response among three alternatives. In the last exercise the items presented once again a structure of geometric solids. Participants were asked to imagine where a person would be located to view the structure from the specific given perspective and to indicate, on aerial view of the structure, its position. The time-limit to complete the tasks was set to 20 min. Overall participants completed the training within the end of the stimulation (M = 16 min; SD = 3.5).

4.4. Procedure

The experiment was carried out in three sessions, each one held in three consecutive days. Participants were randomly assigned to the conditions (10 = online anodal tDCS; 9 = offline anodal tDCS; 8 = sham tDCS). In all cases stimulation lasted 20 min. On *day 1* participants performed the S&M and PF&C tasks to assess baseline visuospatial abilities. A short practice (4 trials per task) was administered immediately before the beginning of the tasks. On *day 2* participants completed the training according to the stimulation condition assigned. The anodal online group underwent the training while receiving tDCS, whereas the anodal offline group faced the training immediately after the end of the stimulation. In case participants in the anodal online condition completed the training before the time-limit, they were asked to wait till the end of the stimulation. In the sham condition half of the participants completed the training while receiving sham tDCS, the other half at the end of the sham stimulation. In *day 3*, hence 24 h after the stimulation and training session, S&M and PF&C tasks were administered again. Fig. 3 depicts the phases of the testing procedure.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.brainres.2017.10.002.

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