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A single tDCS session can enhance numerical competence☆

Maryam Hussain [a,b], Nick J. Davis [b], Yael Benn [b,*]

[a] *School of Health Sciences, University of Manchester, Manchester, M13 9PL, United Kingdom*
[b] *Department of Psychology, Manchester Metropolitan University, Manchester, M15 6GX, United Kingdom*

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ABSTRACT

While numerical skills are increasingly important in modern life, few interventions have been developed to support those with numeracy skills difficulties. Previous studies have demonstrated that applying transcranial Direct Current Stimulation (tDCS) can improve numerical skills. However, tDCS interventions designed to induce lasting changes typically involve reapplying brain-stimulation over several days. Repeated tDCS application can increase the risks associated with the procedure, as well as restricts the transferability of the method to a wider population, particularly those who may experience mobility issues, such as stroke survivors with acalculia. The current study investigated whether a single session of tDCS (anodal to right parietal lobe and cathodal to left parietal lobe), followed by four self-practice sessions without tDCS, could result in enhancement of numerical skills. Nineteen healthy adults ($n = 10$ tDCS, $n = 9$ sham control) implicitly learnt the magnitude association of nine arbitrary symbols, previously used by Cohen Kadosh et al. (2010). Numerical proficiency was assessed using number-to-space task, while automaticity was assessed with numerical Stroop. Results revealed that single-session tDCS had a significant effect on participants' accuracy on the number-to-space tasks, but not on the numerical Stroop task's congruity effect, implying automaticity may require longer practice. We conclude that a single session of tDCS should be considered as an avenue for interventions.

1. Introduction

Despite the high prevalence of numbers and numerical concepts in all aspects of modern life (prices, clocks, pin-numbers, financial/health risk-information), 56% of adults in the United Kingdom have numeracy skills at a level that is expected of a primary school child (National Numeracy, 2019). Adults aged 16 to 65 around the world have an average numeracy score of 269 out of 500, which places them at level 2 or below basic numerical skills (Program for the International Assessment of Adult Competencies, or PIAAC and National Center for Education Statistics, 2012). This includes the ability to calculate with whole numbers and percentages, estimate numbers or quantity, and interpret simple statistics in text or tables. Data from the United States suggest that 30% of Americans are below this level (when asked in English) (Mamedova and Pawlowski, 2020). Furthermore, conditions like developmental dyscalculia or acquired Acalculia (e.g., post stroke or brain injury) result in serious specific difficulty with understanding numbers (Butterworth, 2005; Willmes, 2008; Szűcs and Goswami, 2013; Benn et al., 2022), and can cause significant educational, psychological, employment and well-being difficulties (Parsons and Bynner, 2005; Gross et al., 2009; Benn et al., 2022).

In recent years, non-invasive brain stimulation (NIBS) techniques such as Transcranial Magnetic Stimulation (TMS) have been utilised to study the neural substrates of numerical cognition, by disabling networks and examining the associated impairments to numerical ability (e.g., Göbel et al., 2006; Sandrini and Rusconi, 2009; Sandrini and Rusconi, 2009). NIBS studies have also looked to enhance numeracy skills (Cohen Kadosh et al., 2010; Iuculano and Cohen Kadosh, 2013; Polania et al., 2018; Lazzaro et al., 2022), using transcranial Direct Current Stimulation (tDCS). tDCS uses mild electric currents to modulate brain activity in cortical regions near to the electrodes. In general, brain areas near the anode (positive electrode) become more active, while those near the cathode (negative electrode) are suppressed (Lazzaro et al., 2022).

Cohen Kadosh et al. (2010) investigated whether modulating neural activity with tDCS can affect numerical skills. The between-subjects

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* Corresponding author. Department of Psychology, Manchester Metropolitan University, Brooks Building, Birley Fields Campus, 53 Bonsall Street, Manchester, M15 6GX, United Kingdom.
E-mail address: y.benn@mmu.ac.uk (Y. Benn).

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study demonstrated that anodal tDCS to the right parietal lobe (RPL) and cathodal stimulation to the left parietal lobe (LPL) resulted in enhancement to numeracy skills associated with magnitude processing (mapping between symbols and magnitude) and automaticity of this assignment, whereas the opposite application of current (cathodal stimulation to the RPL and anodal stimulation to the LPL) impaired performance. In other words, the polarity of the brain stimulation (targeting the intraparietal sulcus) specifically facilitated or impaired participants' numerical abilities. The study therefore highlighted the importance of the RPL for processing numerical magnitudes.

The importance of the RPL for magnitude-processing (Cohen and Dehaene, 1995; Price et al., 2007; Rotzer et al., 2008), numerical expertise (Aydin et al., 2007; Parsons and Bynner, 2005) and the development of intact numerical understanding during infancy and early childhood (Hyde et al., 2010; Schel and Klingberg, 2017) has been widely reported. However, several studies, including those using brain-imaging techniques, suggest that the bilateral parietal lobes including the intra-parietal sulcus serve as the neurological substrate of number magnitude processing (Pinel et al., 2001; Fias et al., 2003; Ansari, 2008).

The polarity specificity suggested by Cohen Kadosh et al. (2010) has also been challenged by some NIBS studies (Hauser et al., 2013; Houser et al., 2015). For example, Hauser et al. (2013) and Houser et al. (2015) reported no changes in performance on numerical skills when anodal tDCS was applied to the RPL, and instead enhancement in numerical performance was observed when anodal stimulation was applied to the LPL. However, they did report that polarity specificity is essential when bilateral stimulation is being used. According to the mechanism of tDCS, if cathodal stimulation is applied to the area of the parietal cortex that strengthens numerical abilities, it will suppress cell firing and reduce the area's excitability (Nitsche and Paulus, 2000; Jacobson et al., 2012). Cathodal tDCS causes the resting membrane potential to become more negative as it electrically binds to down-states to hyperpolarize neurons. Therefore, it may impair the individual's numerical skills for several months (Cohen Kadosh et al., 2010; Snowball et al., 2013). However, the discrepancy in polarity can also be explained by the differences in numerical tasks involved in the studies.

Both Hauser et al. (2013) and Houser et al. (2015) focused on enhancing mental arithmetic, while Cohen Kadosh et al. (2010) evaluated numerical skills associated with magnitude-processing of newly learned symbols ('numbers'). These aspects of numerical cognition have previously been associated with different neural substrates. Using functional magnetic resonance imaging (fMRI), it was shown that a left-lateralized pattern of activity is associated with mathematical processing of calculation (Arsalidou and Taylor, 2011; Hauser et al., 2013; Arsalidou et al., 2018), particularly when these are learned facts such as simple additions (Benn et al., 2012). In contrast, magnitude processing depends primarily on the right parietal including intraparietal sulcus (Cohen Kadosh et al., 2007a). Therefore, several studies suggest that both the LPL and RPL contribute to quantity processing and 'core' processes of calculation differently (Dehaene et al., 2003; Cohen Kadosh et al., 2007b; Kaufmann et al., 2011; Benn et al., 2013; Kaufmann et al., 2020).

Evidence suggests that the LPL is likely to be involved in connecting quantitative representation and the verbal code (Dehaene et al., 2008), while the RPL is likely dependent on notation and hence contains non-abstract representations (Cohen Kadosh et al., 2007b). Therefore, it may be argued that established connections between brain regions responsible for diverse numerical components are important to facilitating advanced numerical skills (Kaufmann et al., 2020; Lazzaro et al., 2022). This complex web of brain connectivity for supporting numerical skills emphasises the importance of considering the type of numerical tasks on polarity specificity (Lazzaro et al., 2022).

Numerous cognitive and developmental studies have demonstrated that numerical competency can be assessed by the numerical Stroop test (Rubinsten et al., 2002; Rubinsten and Henik, 2009; Laski and Dulaney, 2015; Jiang et al., 2016; Dadon and Henik, 2017) and the number-to-space paradigm (also known as the number-line task; Booth and Siegler, 2006; Bull et al., 2008). These tasks also represent skills that form the basis of mathematical competence (Cheng and Mix, 2014; Schneider et al., 2018; Sella et al., 2020).

The numerical Stroop task assesses the automatic processing of numbers and their associated magnitudes (MacLeod and Dunbar, 1988; Tzelgov et al., 2000; Cohen Kadosh et al., 2011), which acts as a marker of memory retrieval and quick activation of semantic referents (Logan, 1988; Griffin et al., 1995; Ryalls and Smith, 2000; Cragg, 2016). Consequently, the ability to readily and automatically process numerals plays an important role in the acquisition and implementation of skilled calculations (Laski and Dulaney, 2015; Cragg, 2016).

Conventions for written mathematics rely on spatial relations, and both adults and children are sensitive to these relations (Bull et al., 2008; Wei et al., 2012; Cheng and Mix, 2014; Sella et al., 2020; Atit et al., 2022). The number-to-space paradigm is a robust tool for diagnosing and predicting broader mathematical competence (Opfer and Siegler, 2007; Sella et al., 2015). In this task, participants map a number on a horizontal line. A linear mapping of numbers onto a physical line characterises numerical information competence (Dehaene et al., 2008; Sella et al., 2015).

The current study uses both the numerical Stroop and number-to-space tasks, with the aim of extending the work by Cohen Kadosh et al. (2010), who administered Right Anodal-Left Cathodal (RA-LC) tDCS to $n = 5$ healthy adults (and $n = 5$ sham controls) over five days, while providing them with training for implicitly learning a new-set of 'numbers'. Their results indicated that repeated sessions of cognitive training accompanied by tDCS resulted in improved performance on numerical Stroop and a number-to-space task.

However, reapplying tDCS in multiple sessions over several days restricts the application of the technique to a larger population in realistic settings, as well as making it more costly, and difficult to deliver to clinical populations, who may be lacking mobility e.g., after stroke (Dobkin, 2005; Andrade et al., 2016) or to those who do not live in the proximity of the tDCS resource. For example, it is not uncommon that stroke survivors experience a lack of support and access to other rehabilitative services once they are discharged into the community (Pollack and Disler, 2002; Stroke Association, 2018; Benn et al., 2022), which can compromise their recovery (Johnson et al., 2018). Furthermore, Davis and Koningsbruggen (2013) suggest that multiple sessions of stimulation can result in an unplanned build-up of effects, and that these long-lasting alterations induced by tDCS in cortical excitability could be harmful to the individual (Davis and Koningsbruggen, 2013; Maslen et al., 2014; Davis, 2017).

Therefore, the current study examines alternatives to multiple tDCS application, by exploring the effectiveness of a single tDCS session, followed by four online home-based training sessions. The use of online learning was shown to have high compliance and be effective for improving aspects such as mobility issues in stroke survivors (Johnson et al., 2018), or cognitive skills in children with cancer-related brain injury (Kesler et al., 2011) suggesting that a combination of self-administered online training sessions, and a single tDCS session could be considered for enhancement of cognitive skills in those with developmental or acquired numerical deficits.

In the name of replicability of science, the current study also aims to test (using a larger sample than the study performed by Cohen Kadosh et al., 2010) the efficacy of right-anodal brain stimulation for the mapping between novel symbols and magnitude. Better evidence could be used to optimise the direction of cortical excitability modulations induced by tDCS (Filmer et al., 2014; Polania et al., 2018; Lazzaro et al., 2022), and inform the feasibility of using tDCS to enhance numerical skills. We hypothesise that a single anodal tDCS to the RPL and cathodal stimulation to the LPL, with 1.5 mA intensity of stimulation, followed by 4 online practice sessions, would improve numerical-magnitude processing competence among health adults (measured by performance on numerical Stroop and Number-to-space task) as compared to those who receive sham current.

2. Methods

The study employed a between-groups design where participants received either anodal stimulation to the RPL and cathodal stimulation to the LPL (RA-LC) or sham stimulation. The study received ethical approval from Manchester Metropolitan University (MMU) ethics committee.

2.1. Participants

Nineteen Psychology undergraduate Psychology students (aged 18 to 30, any gender) took part in return for research credits. Participants with dyscalculia or other mathematical impairments or anxieties were excluded from the study. Ten individuals were randomly allocated to the RA-LC group and 9 to the Sham group. Participants were randomly assigned and kept unaware of the type of stimulation they received.

2.2. Procedure

Participants were invited to the lab for the first session, which included a learning task and tDCS (or sham). In the experimental group (RA-LC), a positive electrode was placed over RPL, and the negative electrode over LPL. The control group was set up in the same way, but no current was used for stimulation. For all participants, the session started with the learning task, and tDCS was delivered to the RA-LC group for 20 min from the beginning of the learning task (note that the learning task continued beyond the 20 min of stimulation for further 20–30 min). Following the learning task, participants completed the numerical Stroop test and the number-to-space challenge.

Following the single lab session participants were asked to perform the same training and tests online for four subsequent days. For the online sessions, participants were sent daily reminders to complete the sessions, and were required to provide the researcher with the start and end times of their sessions (but they performed them without the researcher present). Upon completing the last session, participants were debriefed and thanked for their participation. For consistency, and to ensure that participants were familiar with the look and feel of the tasks, all tasks (lab-based or online) were programmed in PsychoPy version 2021.2.3 and uploaded to Pavlovia.org.

2.3. Materials

The study materials were identical to those used by Cohen Kadosh et al. (2010), and originally designed by Gibson et al. (1962). Nine artificial digits were arbitrarily assigned to the numbers 1–9 as shown in Fig. 1.

2.3.1. Learning task

In this task, participants implicitly learned the relationship between the nine arbitrary numerals (Fig. 1) and the corresponding quantity assigned to them. Similarly to Cohen Kadosh et al. (2010), each learning session was divided into 11 blocks, with each block containing 144 symbol pair comparisons (trials), 18 for each adjacent pair. Participants were never explicitly shown or taught the assignement between symbols and digits. The learning occurred via a task in which participants were asked to indicate, by pressing the P (right) or Q (left) keys on a QWERTY keyboard, which of two symbols presented on the screen had, in their view, a greater magnitude. Feedback was provided after every trial, and they were instructed to respond as quickly as possible while avoiding errors. At the beginning of the task, a four-trial practise block was conducted, to ensure participants understood the task. Each trial began with a fixation point, presented in white on a black background, for 300 ms, followed by 300 ms of a blank screen. Then, two symbols appeared on the monitor, one in the left visual field and the other in the right visual field. The stimulus pair was shown for 500 ms or until the participant pressed the P or Q keys. After each response, correct or incorrect feedback was provided for 500 ms. The next trial began 200ms after the feedback. Each block's presentation occurred in a random sequence. The correct response appeared on either left or right an equal number of times, and all pairings appeared equal number of times.

Fig. 1. Number-to-symbol mapping. Participants learned to interpret meaningless symbols (artificial numerals; Gibson et al., 1962) as indicating different magnitudes. The symbols and mappings are identical to those used by Cohen Kadosh et al. (2010).

2.3.2. Number to space task

In this task, participants were instructed to map the novel symbols onto a horizontal line displayed on the screen-examining their ability to recognise the magnitude associated with the symbol. The "1″ symbol was placed at the left end of the line, and the "9″ symbol was placed at the right end (Fig. 2). Participants were instructed to place each of the seven symbols (one at the time) on the line where the symbol 'belongs'. No feedback was given during this task. To remove any response bias induced by stimulus location (Nichelli et al., 1989), the symbols to be mapped appeared in a randomised sequence above the right and left ends of the line (see Fig. 2). Each symbol appeared three times at each side, for a total of 42 trials of symbol placement on a line in each session.

2.3.3. Numerical Stroop task

In the numerical Stroop task, participants were instructed to choose the symbol that is physically larger in size. The Task has three conditions (congruent (e.g., 3 2), neutral (e.g., 3 3), and incongruent (e.g., 2 3)). Given the simplicity of the task (i.e., simply select the physically bigger object), this task tests the automaticity of assigning a symbol to its magnitude, such that if automatic processing of quantity is achieved, it should be reflected in longer response time (RT) and/or higher error rate, as an indication that the magnitude processing interferes with the visual processing task. This should be more obvious for incongruent trials compared to congruent trials, as the meaning of the symbol more directly interferes with what should be a simple visual processing task. The congruency effect refers to the difference in RT and/or accuracy between the congruent, incongruent and neutral conditions (MacLeod and Dunbar, 1988). Neutral trials serve as a baseline, with neutral trial RT and accuracy often falling in the centre (i.e., slower/less accurate

Fig. 2. The participant's task was to place each symbol in order on a line, with the least and greatest symbols provided as anchors. The symbol to be placed appeared above the line, randomly located to the left or right side of the screen.

than congruent trials and faster/more accurate than incongruent trials).

The learned symbols ('digits') appeared on the screen in the same way as they did in the learning task, except the symbols were different in size. Participants were not given feedback and were instructed to select the physically larger symbol as quickly and accurately as possible by pressing the corresponding P or Q keys. While all potential adjacent pairs were used in the learning phase (e.g., 1–2, 2–3, 3–4), only non-adjacent pairings were used to test automatic numerical representation creation (e.g., 1–3, 2–4, etc), as suggested by Tzelgov et al. (2000). The symbols for 1 and 9 received the same classification (small and big, respectively) throughout the learning task and were thus omitted from the Stroop task (Tzelgov et al., 2000) to avoid stimulus-response learning. The correct answer appeared an equal number of times on the right and left visual fields. Due to a technical error, the number of trials of the neutral, congruent and incongruent conditions slightly differed. While the neutral condition had 108 trials, the number of trials in the other two conditions varied between 168 and 172.

2.3.4. tDCS

Following the 10–20 EEG guide, electrodes were placed across the LPL and RPL at P4 and P3, respectively (Koessler et al., 2009). Unlike Cohen Kadosh et al. (2010), who used 3 × 3 cm electrodes and stimulated participants with 1 mA, the current study used 5 × 5 cm electrodes and 1.5 mA for stimulation. The reasoning for this change was to compensate for a single session of tDCS stimulation as compared to five sessions of brain stimulation. Another reason was to limit the confounding variable of inter-subject variability in response to tDCS (Batsikadze et al., 2013; Horvath et al., 2015; Davis, 2021). Fig. 3 shows a model of the electric field generated with the above parameters using the ROAST toolbox for Matlab (Huang et al., 2019).

For the RA-LC group, the current was slowly increased to the stimulation intensity (1.5 mA) during the first 15 s of stimulation (ramp-up), and then gently lowered to 0 mA during the last 15 s of stimulation (ramp-down). At the start of the learning activity, which lasted 40–50 min, a continuous direct current (1.5 mA) was given for 20 min between the ramp-up and ramp-down. The sham group experienced 30 s of stimulation made of 15 s of ramp-up and 15 s of ramp-down. tDCS was administered in accordance with established safety guidelines (Ko, 2020). A pair of saline-soaked sponge electrodes were used to deliver the current. Although stimulation had ended during the learning task, electrodes were left in place until all tasks were completed to minimise participants' disruption and bias. At the start of the stimulation, some respondents (from both groups) reported a faint tingling sensation that quickly faded. No other side effects or discomforts were reported.

3. Results

One participant from the Sham group did not engage during numerical Stroop task (response accuracy during home-practice sessions was on average 63.7%, which is at chance level), and therefore, their data was excluded from the analysis, leaving $n = 10$ in the tDCS group, and $n = 8$ in the sham group. For numerical Stroop task and number to space task only, data for one of the sessions was missing for two participants from RA-LC group due to a technical errors.

3.1. Learning task

To examine progress on the learning task, changes in Reaction Time (RT) and accuracy were evaluated over the 5 sessions. Fig. 4b and Table 1 shows that the RA-LC group had more correct responses in comparison to the sham group, such that as participants took more training sessions, those in the RA-LC group performed more accurately compared to the control group. As illustrated in Fig. 4b, session 1 created the gap between the groups that was then maintained and strengthened across sessions.

To evaluate the mean and standard deviation (SD) for RT and Accuracy (Table 1) in each group, repeated measures ANOVA was conducted. There was a clear reduction in RT over the sessions for both Sham and RA-LC groups, $F(4, 64) = 25.39$, $p < .001$, $\eta^2 = 0.613$, but there was no difference in RT between the groups, $F(4, 64) = 0.11$, $p =$

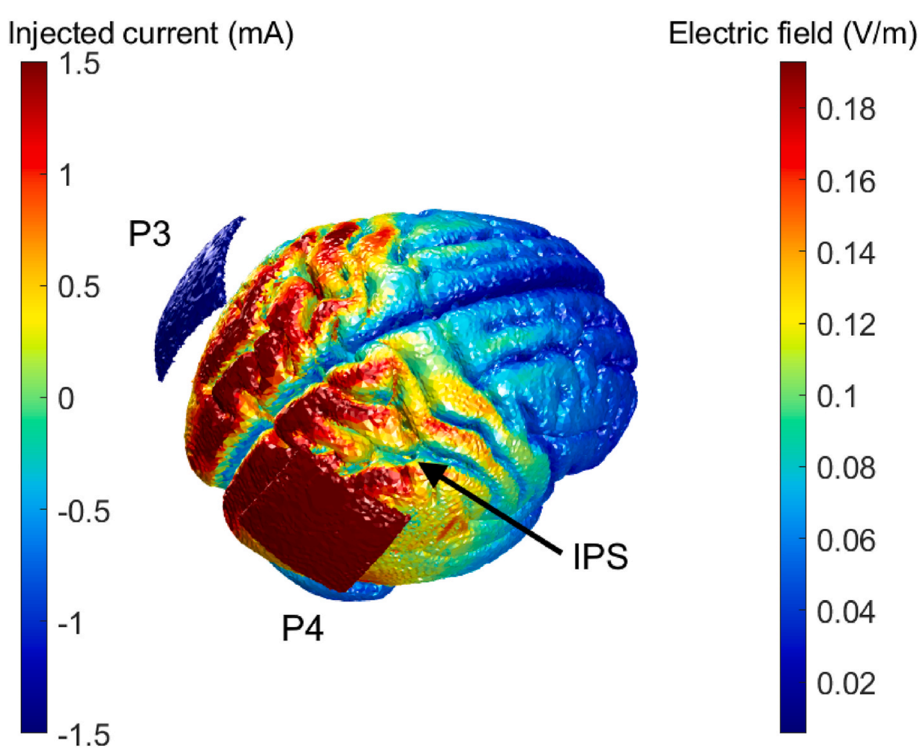

Fig. 3. Model of the magnitude of the electric field on the brain surface, resulting from tDCS stimulation over P3 and P4 of the International 10-10 system. The electrode montage was designed to overlay the dorsal part of the intraparietal sulcus (IPS).

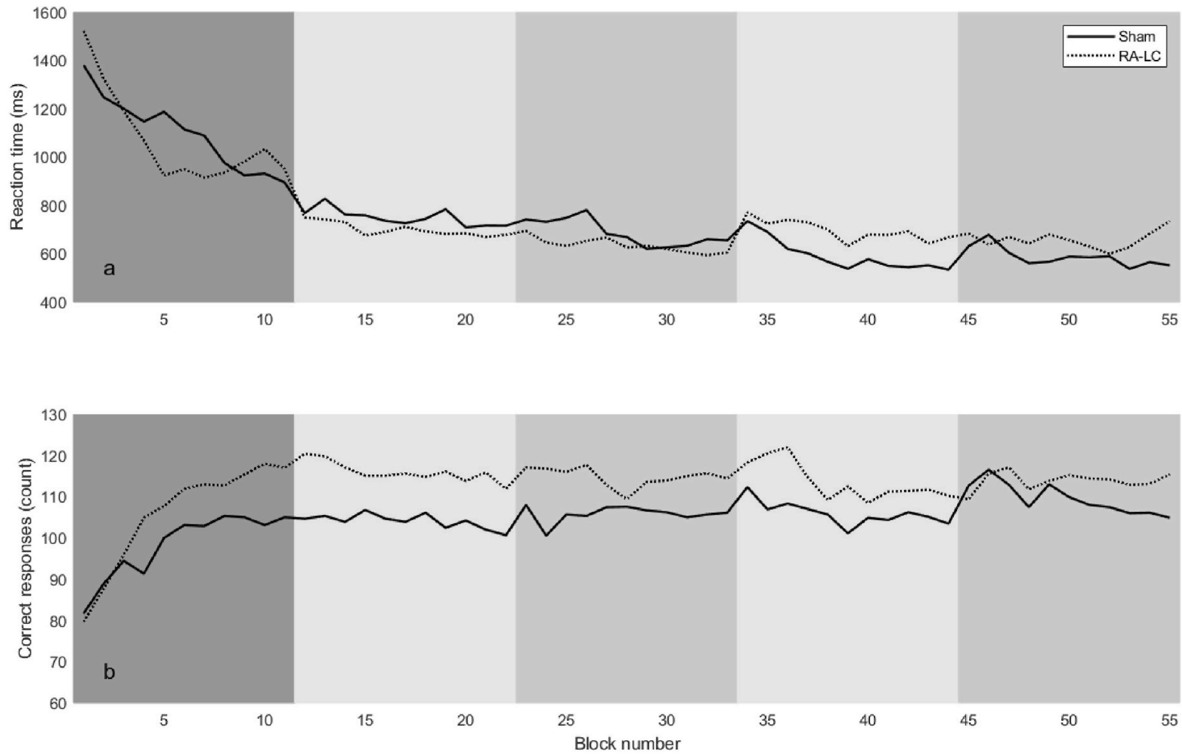

Fig. 4. Changes in reaction time and number of correct responses in the RA-LC and the Sham groups. Fig. 4a illustrates the reduction in reaction times across blocks of trials for both groups. Fig. 4b illustrates the count of correct responses per block. The shaded bands represent the five sessions, each of which contained 11 blocks of trials. The first session (shaded darker than others), took place in the lab with tDCS or sham stimulation, while subsequent sessions took place in participnats' chosen space and time.

Table 1
Mean and standard deviation (SD) of reaction times (RT) and accuracy for the learning task for RA-LC and sham groups across the 5 session.

		1st session	2nd session	3rd session	4th session	5th session
RA-LC	*Mean RT*	1064.20	664.07	619.65	610.57	542.22
	SD	311.82	190.29	187.57	220.73	236.93
	Mean Accuracy	73.47	80.53	79.70	78.93	79.10
	SD	13.41	13.69	14.97	19.86	18.67
Sham	*Mean RT*	1092.68	725.41	644.16	594.65	555.10
	SD	399.71	304.97	338.57	263.96	235.01
	Mean Accuracy	69.01	73.67	74.87	74.33	76.95
	SD	19.36	19.33	22.07	21.57	20.82

.98. Both Sham and RA-LC groups had significantly improved accuracy over the sessions, $F(4, 64) = 6.52$, $p = .004$, $\eta^2 = 0.667$, but there was no interaction between session number and stimulation condition, $F(4, 64) = 0.52$, $p = .720$. This indicates that both groups reduced RT and improved accuracy across the sessions but the effect of stimulation was not significant in the learning task.

To examine differences in progress on the learning task between the sham and the RA-LC groups, the power-law function: RT = B* (N)$^{-C}$ (Newell and Rosenbloom, 1981; utilised by Cohen Kadosh et al., 2010) was used to evaluate changes in RT for each participant as they progressed through the sessions and the blocks within each session during the learning task. In the formula, RT stands for the average response time in each block, B for the mean RT for all items on the first block only, N for the block number (range between 2 and 55), and C represent the performance of learning slope for each participant. The data from the power-law function was entered into a non-linear regression. For both groups, results from the non-linear regression revealed a comparable fit (RA-LC, $R = 0.90$; Sham, $R = 0.93$, as shown in Fig. 4a). This is comparable to the fit found by Cohen Kadosh et al. (2010) (RA-LC, $R = 0.88$; Sham, $R = 0.85$). The slope of the line of best fit through the Sham data was −9.96, whereas that for the RA-LC data was −9.38. A *t*-test comparing the two regression lines for RT, revealed a significant difference ($t(106) = 5.68$, $p < .001$), such that the RA-LC group showed significantly higher learning rate compared to the sham group (Fig. 4).

3.2. *Number-to-Space task*

To evaluate the size of error performed by the tDCS and sham groups (i.e., how far was the number placed from its target) we performed two different analysis. First, we compared the average absolute error on each of the quantities between the group (Fig. 5a), and compared the average absolute error on all digits combined between the groups. Results of a two-tailed *t*-test revealed that the RA-LC had significantly lower mean error: $t(17) = 2.19$, $p = .043$.

We further used a linear function with the number of correct responses across all session, such that the target number was plotted against the mean location of the number as it was actually placed by participants (Fig. 5b). Results revealed that the linear function of the RA-LC group more strongly predicted performance on this task compared to the linear function of the sham group, which was relatively poor, except for the symbols representing the middle of the range (numbers 4 and 5). The slope of the line of best fit through the Sham data was 0.3, whereas that for the RA-LC data was 0.93. These differences were significant ($t(10) = 8.60$, $p < .001$), with the RA-LC group being significantly closer to a slope of 1.0, which represents perfect performance.

3.3. *The Numerical Stroop task*

The numerical Stroop task was used to examine the acquisition of automaticity in assigning novel symbols ('numerals') to their respective

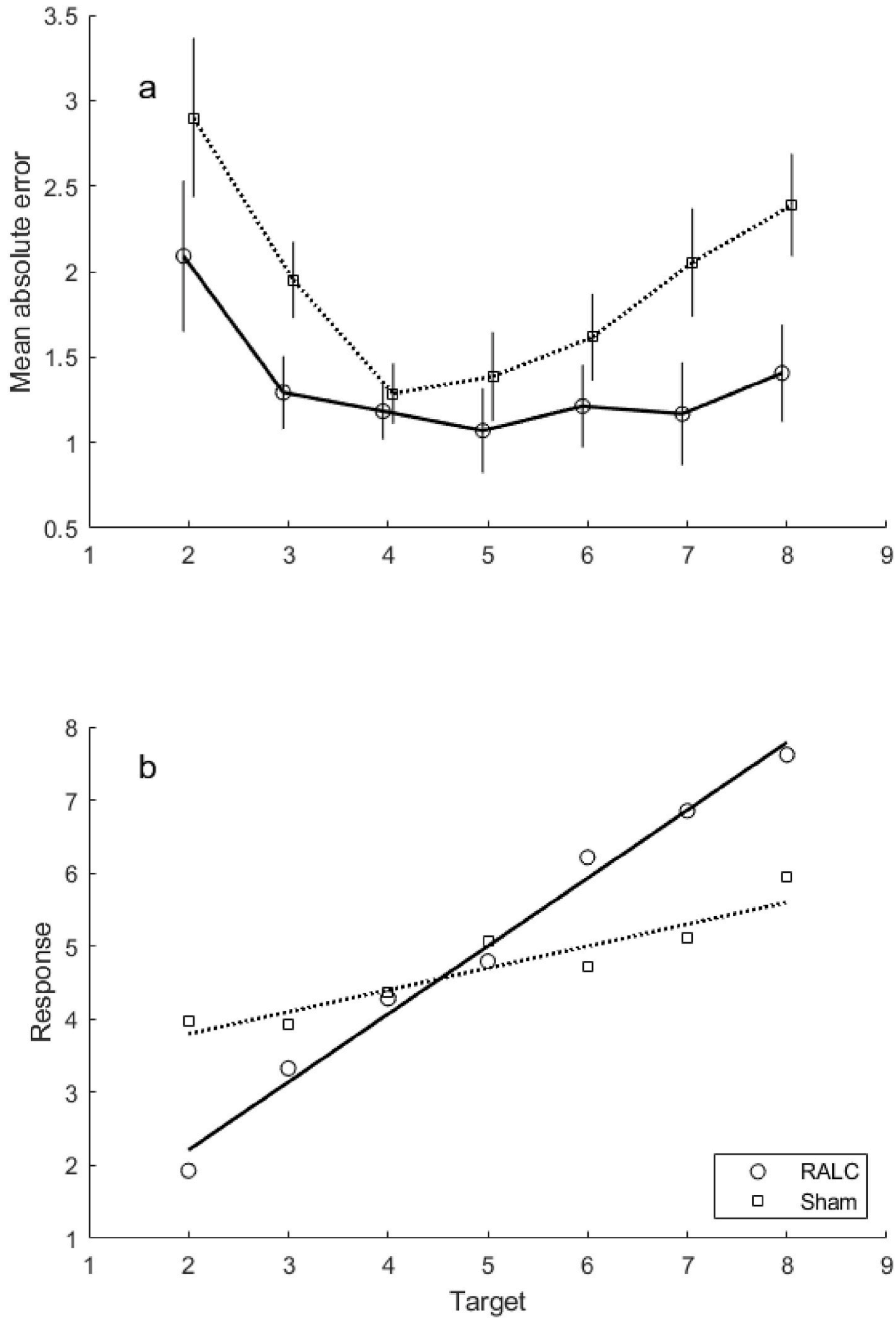

Fig. 5. Number-space mapping. In Fig. 5a the mean absolute error is shown at for each target number position. Participants in the Sham group show significantly higher error. In Fig. 5b the relationship between 'expected' and 'actual' number space mapping is shown. Here individuals in the RA-LC group (circles, solid line) achieved significantly better performance than the those in the Sham group (squares, dashed line), with the participants' responses lying closer to the target slope of 1.0. These best fit lines show a clear difference in accuracy between RA-LC and Sham groups.

magnitude. If magnitude processing has become an automated process, it would interfere with the purely visual perception task of selecting the physically larger 'digit.' This interference could be observed through either higher RT (i.e., slower response time) or lower accuracy, particularly on the incongruent compared to congruent condition.

To examine performance on the Stroop task, we examined the mean and SD for RT (Table 2), and Accuracy (Table 3) in each group, and illustrated this data in Fig. 6. There was a clear reduction in RT over the sessions for both Sham and RA-LC groups, $F(4, 56) = 16.13, p < .001, \eta^2 = 0.535$, but there was no significant difference in RT between the groups, $F(4, 56) = 1.05$, $p = .389$. Results further indicated that there was no RT congruity effect observed for participants in either sham or RA-LC groups, as both groups failed to show significantly increased RT for incongruent compared to congruent or neutral trials over time $F(8, 112) = 1.22$, $p = .294$. This is in contrast to Cohen Kadosh et al. (2010), who noticed the congruity effect from the third session onwards for the RA-LC group and the fourth session for the Sham group.

A repeated-measures ANOVA on accuracy was conducted with congruency and session number as within-subject factors, and a between-subjects factor of stimulation condition. None of the main effects or interactions was statistically significant in this analysis. This lack of effect likely reflects a ceiling effect, as the overall accuracy for the

Table 2
Mean reaction times (RT) and standard deviation (SD) in the Numerical Stroop Task for the RA-LC and Sham groups across the 5 sessions.

			1st session	2nd session	3rd session	4th session	5th session	*Overall Mean*
	Congruent	*Mean*	617.43	514.91	443.23	439.93	411.23	484.11
		SD	152.45	119.95	66.79	139.35	52.24	132.41
RA-LC	Neutral	*Mean*	597.54	505.01	434.27	439.25	410.79	476.22
		SD	136.30	109.17	64.72	139.70	49.41	123.24
	Incongruent	*Mean*	602.70	513.48	437.37	436.29	414.82	479.58
		SD	168.98	150.38	75.76	129.10	53.57	136.99
	Congruent	*Mean*	611.37	481.88	492.71	460.66	450.91	499.51
		SD	137.86	102.39	73.02	79.98	87.49	110.48
Sham	Neutral	*Mean*	578.83	477.14	492.62	442.32	446.34	487.45
		SD	138.96	107.37	70.23	71.87	92.56	106.73
	Incongruent	*Mean*	604.89	478.10	507.17	443.70	445.84	495.94
		SD	157.34	103.01	86.83	70.63	81.99	115.77

Table 3
Mean accuracy % and standard deviation (SD) in the Numerical Stroop Task for RA-LC and Sham groups across the 5 session.

			1st session	2nd session	3rd session	4th session	5th session	Total
RA-LC	Congruent	Mean	95.4	82.69	94.19	89.48	91.16	90.74
		SD	5.19	31.81	5.36	10.93	9.33	15.41
	Neutral	Mean	93.05	78.09	93.24	90.93	91.57	89.61
		SD	14.07	32.21	4.52	9.58	8.68	16.63
	Incongruent	Mean	89.23	72.75	93.93	89.29	91.13	87.56
		SD	23.73	38.91	3.88	12.38	9.32	21.43
Sham	Congruent	Mean	97.11	92.82	95.37	95.6	95.49	95.28
		SD	2.99	9.07	3.21	2.74	4.52	5.02
	Neutral	Mean	96.45	91.82	96.91	95.37	95.22	95.15
		SD	3.18	10.3	1.72	3.15	4.77	5.43
	Incongruent	Mean	97.77	93.75	95.91	95.76	95.39	95.71
		SD	1.93	8.47	2.26	3.3	6.82	5.14

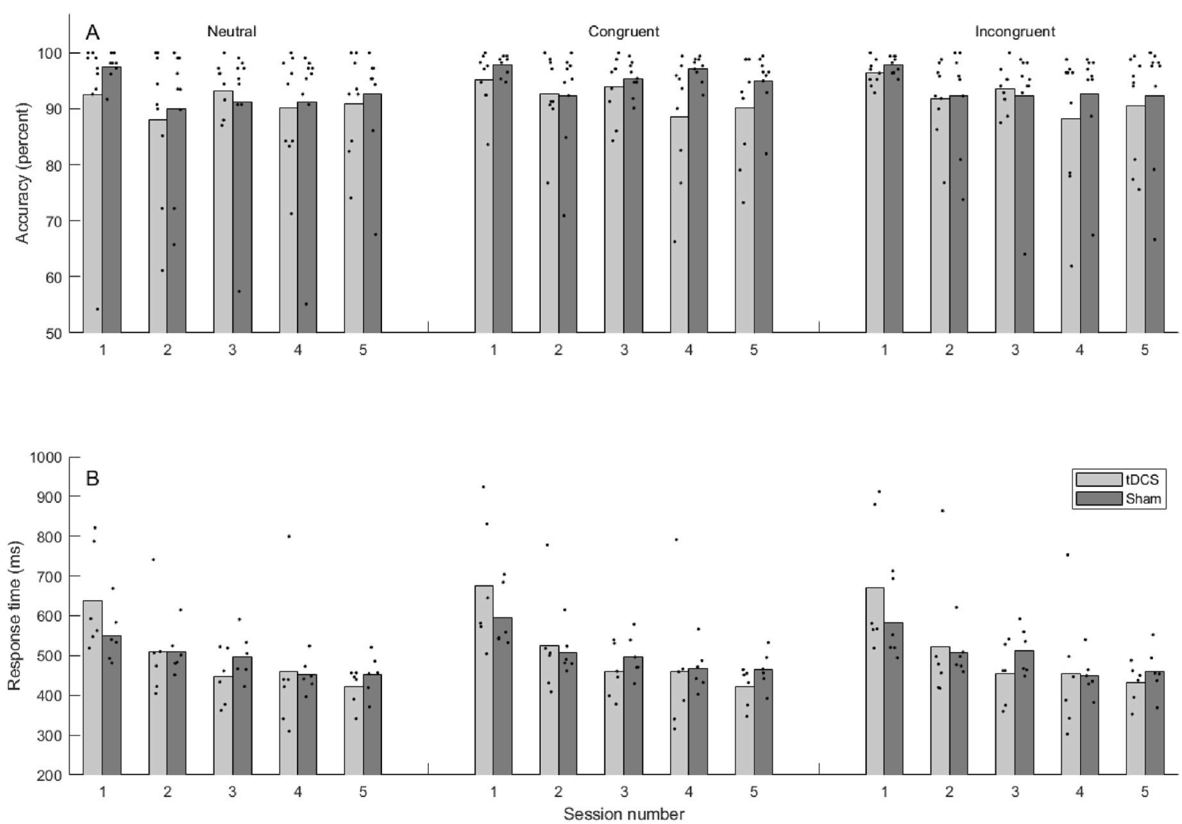

Fig. 6. Accuracy (panel A) and response time (panel B) for the Stroop task in the different conditions (Neutral, Congruent and Incongrunet) across the two groups (RA-LC and Sham). Mean values are represented by the bars, (light bars represent RA-LC, dark bars represent the Sham condition) while individual data is shown as points.

Stroop task was generally over 90% (as seen in Fig. 6).

3.4. Correlation between all tasks perfromances

To further explore the effect of tDCS on numerical processing, we examined the correlation between performances on the three tasks (learning, number-to-space and Stroop tasks) at Session 5 (the final session).

As shown in Table 4, the correlations generally took a different sign in the different groups (i.e., while in the sham group improved performance on one task was negatively correlated with performance on other tasks, in the tDCS group the relationships were positive). However, this difference only reached statistical significance for the correlation of Number-to-Space and Learning Task accuracy, and for the Number-to-Space and Stroop Accuracy (as assessed using Fisher's Z-transform).

4. Discussion

The current study represents a partial replication of Cohen Kadosh et al. (2010) but it focused on whether results could be achieved without 5 sessions of tDCS, but rather with a single anodal tDCS to the Right Parietal Lobe (RPL) and cathodal stimulation to the Left Parietal Lobe (LPL), followed by 4 sessions self-practice delivered online. The motivation for this focus is to improve the transferability of tDCS for numerical enhancement among populations who may have limited access to repeated sessions in the lab, and to reduce the risk associated with repeated application of tDCS (Davis, 2017). Participants in the current study implicitly learnt the magnitude relationship of nine symbols and the quantity attributed to them (Cohen Kadosh et al., 2010). In each of the five session, following the learning stage, a numerical Stroop task was administered to assess the automaticity of the newly learned digits (MacLeod and Dunbar, 1988; Tzelgov et al., 2000; Cohen Kadosh et al., 2011). This was followed by the number-to-space task, which assessed participants' mental representation of numbers (Booth and Siegler, 2006; Bull et al., 2008).

The findings show that a single session of anodal stimulation to the RPL and cathodal stimulation to the LPL, followed by 4 online self-training sessions, improved the acquisition of quantity assignment to novel symbols, previously only demonstrated with the use of multiple tDCS sessions (Polania et al., 2018; Lazzaro et al., 2022). Hence, the current findings open the possibility for tDCS to be more easily used for enhancing numerical cognition among groups for which travel to the lab may be a barrier (e.g., stroke survivors with acalculia, Benn et al., 2022), and could be considered for all groups while reducing the risks associated with multiple tDCS sessions (Davis, 2017).

Given that the current study models cognitive mechanisms that are required for learning numeracy skills during early childhood (Rubinsten et al., 2002; Cohen Kadosh et al., 2010; Schel and Klingberg, 2017), it strengthens the existing evidence that indicates that the RPL is essential for the development of assignments between numbers' symbols and magnitude (Price et al., 2007; Cohen Kadosh et al., 2007a, 2011; Schel and Klingberg, 2017). More specifically, our finding show that by the final session, performance of participants in the tDCS group was positively correlated with performance on the training task, while in the sham group these corrrlations were negative. It is not clear why this may be the case, but these were not significant. However, importantly, the difference in patterns of performance between the groups were significant, suggesting that the RPL is involved in enabling the learning of mapping between symbols and magnitude representations. The findings also support the specificity of current polarity as suggested by Cohen Kadosh et al. (2010). The observed discrepancy in polarity in later studies (Hauser et al., 2013; Houser et al., 2015) may therefore be due to variations in numerical tasks; While Houser and colleagues tested participants with a mental arithmetic task, Cohen Kadosh et al. (2010) and the current study focused on the assignment of magnitude to novel symbols (numbers).

Table 4
Correlation coefficients among study variables, for the Sham group and the RA-LC group. Differences in correlation direction are assesed using Fisher's Z-transform.

Correlation	r (Sham)	r (RALC)	Difference
Learning Task Accuracy – Number-Space Accuracy	−.595, p=.159	.450, p=.192	Z = 1.867, p = .031
Learning Task Accuracy – Stroop Accuracy	−.068, p=.886	.487, p=.154	NS
Number-Space Accuracy – Stroop Accuracy	−.663, p=.105	.238, p=.507	Z = 1.778, p = .038

In particular, the findings show that tDCS stimulation resulted in improved accuracy compared to sham condition, when mapping of symbols to a number line. The intervention group was better able to make the required transitive inference and understand the ordinal properties of the new symbolic system. The findings on the number-to-space task are consistent with Cohen Kadosh et al. (2010) and it enhances these findings by demonstrating that even a single session of brain stimulation can induce a performance that is characterized by a linear fit. This fit is usually dependent on exposure to critical educational material (Rubinsten et al., 2002; Dehaene et al., 2008), and participants in the intervention group have developed the internal number line representation.

However, contrary to our hypothesis, a single session of tDCS followed by repeated online sessions did not result in automaticity effects for the numerical Stroop task. Both the intervention and the control groups failed to show the development of automaticity, as reflected by differences in response time (or accuracy) between congruent and incongruent Stroop items. These findings are inconsistent with previous findings, which observed a congruity effect in both the tDCS and the sham condition (from a later session), (Cohen Kadosh et al., 2010).

There could be several explanations for the differences in performance between the two studies. Several studies have highlighted that tDCS enhancement in a task may come at the cost of another task (Davis, 2017; Iuculano and Cohen Kadosh, 2013; Maslen et al., 2014), such that increased cognitive performance can be associated with poorer performance on a different cognitive task. Despite both tasks being indices of numerical magnitude proficiency, they require different mechanisms. While the number-line task has an algorithmic mechanism (Sella et al., 2020), the numerical Stroop task requires a memory-based mechanism (Logan, 1988; MacLeod and Dunbar, 1988; Ryalls and Smith, 2000). Furthermore, the compared judgement decision for these two tasks differs (Rubinsten et al., 2002). It can be suggested that performance on the number-line task came at the cost of performance on the numerical Stroop task. However, as this was not observed in the original study, it is unlikely to be the case.

A more likely explanation stems from the observation that automaticity requires more time to develop compared to ordinality. For example, young children show an ordinal knowledge of numbers before formal education (Sella et al., 2019), while the size congruity effect appears later around grades 3–5 (Girelli et al., 2000). According to Rubinsten et al. (2002), young children establish the algorithm-based mechanism that utilises the internal scale throughout their first six years of life. This algorithm-based process can be observed in pupils in the first grade, through models such as the number-to-space task (Sophian, 2000). The size congruity effect on the other hand, develops later and is not fully developed at the beginning of first grade (Rubinsten et al., 2002; Cragg, 2016). Hence, it can be implied that participants in the current study simply needed more practice sessions (and this effect may be compounded with the online delivery of sessions). Given the small number of sessions, most of which were in home settings (and practiced by low-motivation student sample), it is perhaps not surprising that automaticity was not achieved.

Motivational aspects may be combined with the integration of online sessions in the methodology. According to Logan (1988), automaticity reflects direct retrieval of numerals classification (large or small) from memory. The development of automaticity and congruity effect are particularly sensitive to attentional requirements (Logan, 1988; Ryalls and Smith, 2000; Rubinsten et al., 2002). Wammes and Smilek (2017) suggest that participants' mind wandering is increased during online learning, affecting their capacity to pay attention, which impacts their memory performance (Varao-Sousa et al., 2018). It may therefore be implied that participants in Cohen Kadosh et al.'s (2010) study may have benefited from having the sessions provided in person (Varao--Sousa et al., 2018; Wammes and Smilek, 2017), in contrast to the current study, where participants had learning sessions online.

Furthermore, the sessions' start times varied greatly between participants in the current study. While some participants began their online sessions late at night (around 1 a.m. or 2 a.m.), all participants in Cohen Kadosh et al.'s (2010) study had their sessions between 9 a.m. and 6 p.m. The timing of the training could have affected memory (Barbosa and Albuquerque, 2008) and hence automaticity. According to Chellappa et al. (2019), circadian misalignment reduces the capacity for sustained attention and visual-motor function. While this may need further investigation, it is likely that groups that are offered tDCS as intervention for cognitive numerical difficulties will be more motivated and focused even when using online sessions. This point may require further investigation, so that future intervention comes with recommendation for 'ideal' practice time.

Nevertheless, the current findings have important implications for numerical cognition theories. According to Rubinsten et al. (2002), people develop two different representations of numerical quantities. The first representation is an internal number line that can be accessed by an algorithmic and intentional process, and the second representation is composed of instances of numerals being classified as large or small. This representation can be retrieved automatically through instance awakening, which is based on memory. The automaticity of classifying digits as large or small is dependent on the accumulation of occurrences in memory, which allows such classification to be recovered from memory in a single step (Logan, 1988). While Rubinsten and colleagues' (2002) model has been challenged due to methodological flaws (Jiang et al., 2016), the current findings may provide support for the two representation models theory using different numerical tasks from those used by Rubinsten et al.'s (2002). Our findings imply that individuals develop two different representations of numerical quantities (or at least, that these skills are developed in stages) as the tDCS group demonstrated more advanced development of the first representation through improved performance on the number-to-space task, but no significant development of the second representation as demonstrated by their performance on the numerical Stroop task.

Unlike Cohen Kadosh et al., we have not been able to test the participants after six months to examine the maintenance effect of a single-tDCS session effect. Furthermore, we have not sufficiently verified (by asking participants following the study) that participnats were blind to their experimental condition (though anecdotal conversation with some participants suggested they did not know which condition they were assigned to). Future studies should ensure blind assignment when investigating the long-term effects of a single session of tDCS on healthy adults, as well as the effects of a single tDCS session for improving numerical skills among those with limited numeracy abilities. This will improve the transferability of present findings to clinical population such as stroke survivors (Benn et al., 2022) or those with developmental dyscalculia (Lazzaro et al., 2022). The adoption of different numerical strategies at different stages of development might suggest a critical period for effective intervention using brain stimulation in children at risk of mathematical difficulties. It is suggested that this may be a promising avenue for future research, although there may be ethical and technical difficulties to consider (Davis, 2014; Maslen et al., 2014).

Overall, the current study offers an encouraging way forward for speeding up and improving the transferability of tDCS to clinical setting. Our results show that a single tDCS session, followed by four online self-training sessions, significantly improved the acquisition of new symbol-magnitude mapping. The failure to develop the congruity effect in the numerical Stroop task can be explained by the observation that automaticity needs more time to develop in comparison to the internal number line (Logan, 1988; Ryalls and Smith, 2000; Rubinsten et al., 2002). Future research should focus on investigating the long-term effect of such single session application, and also whether automaticity can be improved with more self-training sessions, or by limiting the timing of sessions so that they are taken at optimal learning times. Future research could also explore whether different cognitive training can result in improved numerical competence. For example, attention problems could be minimised or even excluded by adjusting the numerical Stroop task such that individuals are asked to select the bigger numerical magnitude rather than larger physical size (Dadon and Henik, 2017). As the field of tDCS-based cognitive enhancement is still relatively new (Lazzaro et al., 2022), further research is needed to thoroughly examine the advantages and transferability of this technology to the wider population. Understanding the link between enhancement and its possible transferability can lead to intriguing prospects for cognitive enhancement in both healthy and atypical individuals with low numeracy skills.

CRediT authorship contribution statement

Maryam Hussain: Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing - original draft. **Nick J. Davis:** Data curation, Formal analysis, Methodology, Supervision, Validation, Visualization, Writing - review & editing. **Yael Benn:** Conceptualization, Methodology, Supervision, Validation, Writing - review & editing.

Data availability

we have shared the data on the OSF site of this article

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