

Brain stimulation enables the solution of an inherently difficult problem

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ABSTRACT

Certain problems are inherently difficult for the normal human mind. Yet paradoxically they can be effortless for those with an unusual mind. We discovered that an atypical protocol for non-invasive brain stimulation enabled the solution of a problem that was previously unsolvable. The majority of studies over the last century find that no participants can solve the nine-dot problem – a fact we confirmed. But with 10 min of right lateralising transcranial direct current stimulation (tDCS), more than 40% of participants did so. Specifically, whereas no participant solved this extremely difficult problem before stimulation or with sham stimulation, 14 out of 33 participants did so with cathodal stimulation of the left anterior temporal lobe together with anodal stimulation of the right anterior temporal lobe. This finding suggests that our stimulation paradigm might be helpful for mitigating cognitive biases or dealing with a broader class of tasks that, although deceptively simple, are nonetheless extremely difficult due to our cognitive makeup.

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1. Introduction

Our minds are well adapted to deal with those problems that have ecological significance, even if they are computationally challenging; whereas we consistently struggle with certain cognitive biases, even if we are taught to avoid them [15]. Intriguingly, the opposite can be true for those with an unusual mind. For example, certain savants can perform esoteric numerical calculations while being deficient in elementary arithmetic [27]. And, they can have extraordinary veridical memories while struggling to get the gist of a story or recognize familiar faces [27].

Interestingly, there is evidence that such unusual ability is associated with left hemisphere inhibition together with right hemisphere facilitation [29]. This inspired us to investigate whether transcranial direct current stimulation (tDCS), by diminishing left hemisphere dominance, could enable solving a problem that is extraordinarily difficult for the normal human mind. Specifically, we predicted that cathodal stimulation (decreasing excitability) of the left anterior temporal lobe (ATL) together with anodal stimulation (increasing excitability) of the right ATL ('L – R+' stimulation) could enable healthy participants to solve the nine-dot problem (see Fig. 1), a problem that is almost unsolvable due to our cognitive makeup [16]. This prediction is based on recent evidence that such

tDCS protocol can significantly improve insight problem solving, possibly by mitigating the so-called 'mental set' effect [6].

2. Materials and methods

2.1. Participants

From our pilot study (see below), we determined that the most efficient experimental design for testing our hypothesis, with a 95% statistical power, was to have 2 stimulation groups in our main experiment ('sham stimulation' for placebo control versus 'L – R+' stimulation), each with 11 subjects. We recruited 28 healthy right-handed participants aged between 19 and 63 years from the University of Sydney community, with six participants excluded due to previous experience with the nine dots problem. Participants were also 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. The study was carried out to conform to the principles of the Declaration of Helsinki and was approved by the University of Sydney Human Research Ethics Committee. All participants gave written informed consent for the study prior to the experiment. None of the participants experienced adverse effects as a result of tDCS.

2.2. Transcranial direct current stimulation (tDCS)

tDCS involves applying a weak direct current to the scalp via two saline-soaked sponge electrodes, thereby polarizing the underlying brain tissue with electrical fields [18]. Although it is controversial how focal the effects of tDCS is [10,22], recent neuroimaging studies [19,34] demonstrate that tDCS does modulate cortical excitability and changes in cerebral blood flow at the stimulated region under the electrodes. Bearing in mind that effects of brain stimulation can be sensitive to mental state [24] and that stimulation is known to be more effective if applied during performing relevant tasks [1], we had a simple experimental design in order to minimize potential distractions (e.g. unrelated control tasks, neuroimaging) from the nine-dot problem.

We used a custom made, battery-driven, constant current stimulator with a maximum output of 2 mA and 2 sponge electrodes each with an area of 35 cm².

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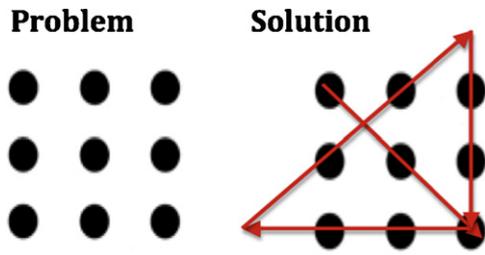


Fig. 1. The task is to connect all nine dots with four straight lines, drawn without lifting pen from paper or retracing a line. The majority of published studies show that no participants can solve this deceptively simple problem [16] – a fact we confirmed. But with 10 min of our stimulation protocol, more than 40% of healthy participants did so.

For the active (L–R+ stimulation) condition, a constant current of 1.6 mA intensity was applied, and was manually and slowly ramped up (over 30 s). Specifically, for L–R+ stimulation, we applied cathodal tDCS at the left anterior temporal lobe (ATL) together with anodal tDCS at the right ATL for approximately 10 min, which is believed to affect cortical excitability for about an hour [18]. Our stimulation protocol, based on the model of inter-hemispheric rivalry [21,28], is critically discussed in Chi and Snyder [6]. It is consistent with recent modelling and behavioural evidence that bilateral tDCS at the temporal lobes is effective for modulating hemispheric dominance [31], leading to left lateralization and an enhanced reading ability.

For the sham stimulation (placebo control) condition, the sponge electrodes were placed in the same positions as in active stimulation, but after 30 s, the electrical current was covertly ramped down to off. This procedure is known to produce sensations virtually indistinguishable from that in the active condition [11,18].

2.3. The nine-dot problem

The task asks the participants to connect all nine dots with four straight lines, drawn without lifting pen from paper or retracing a line (see Fig. 1). A century of research has established that “the expected solution rate for this problem under laboratory conditions is 0%” [7,16]. “This ‘nine-dot’ problem is known to be so difficult that most people fail to solve the problem even if they are given hints, a long time to solve the problem, or 100 attempts to solve the problem [16,33].

2.4. Procedure and tasks

Participants were given a total of 9 min to solve the nine-dot problem [7,16]: 3 min ‘before’ stimulation, 3 min (‘online’) during stimulation and 3 additional minutes (‘offline’) immediately after the stimulator was turned off.

All task stimuli were shown on a 21.5 in. Apple iMac with a viewing distance of approximately 30 in. However, participants were asked to attempt the nine-dot problem by pen and paper and were allowed unlimited attempts for 3 min to solve the problem.

Participants were also given a simple arithmetic control task each time prior to attempting the nine-dot problem. This task involved answering as many 2-digit addition arithmetic problems (e.g. $51 + 23$) as possible in 2 min. Its score (the number of correct answers) provides an indication of reaction time and quantitative ability. Participants were required to type in the right answer on the keyboard before they could move on to the next problem.

During the ‘online’ phase, participants were given the control task and the nine-dot problem only after they have received 5 min of tDCS. This was to ensure that there was sufficient change in cortical excitability [18]. During this 5-min period, participants were asked to do a distraction task where they had to spot the one difference between two very similar pictures, by clicking at the difference on the computer screen.

2.5. Statistical analysis

Since our prediction is based on Chi and Snyder [6], and also the results of the pilot study, a one tailed Fisher’s exact test is used to compare the solution rate between the sham stimulation group and the L–R+ stimulation group. Furthermore, binomial distribution is used to compare the observed solution rate in the L–R+ stimulation group and the expected solution rate for the nine-dot problem (our analysis used an overly conservative estimate of 5% – the majority of studies reported a solution rate of 0%, although there have been a few studies reporting a solution rate of 5%).

2.6. Pilot study

Prior to the experiment reported here, we performed a pilot study in order to determine the necessary sample size and the experimental design. We replicated the stimulation protocol as in Chi and Snyder [6], with 7 participants in each of the

Table 1
Demographic characteristics across the two stimulation groups.

	‘Sham’	‘L–R+’
Age (years)	31.4 ± 4.6	29.8 ± 3.0
Gender (number of males/the total number of participants)	4/11	5/11
Baseline score in the arithmetic control task	25.4 ± 2.5	25.1 ± 3.6
Score in the arithmetic control task after stimulation (‘Offline’)	26.2 ± 3.7	26.5 ± 3.8
Experience in a quantitative field (number of participants)		
Limited experience	5	5
Average experience	5	2
Significant experience	1	4

Values are presented as mean ± standard error of the mean. Participants across the two stimulation groups did not differ in terms of age ($p = 0.65$, 2 tailed independent t -test), gender ($p = 1$, 2 tailed fisher’s exact test), baseline score in the arithmetic control task ($p = 0.95$, 2 tailed independent t -test) or experience in a quantitative field ($p = 0.27$, 2 tailed fisher’s exact test). Furthermore, there was no change in the scores of the arithmetic control task as a result of sham stimulation ($p = 0.74$, 2 tailed paired t -test) or L–R+ stimulation ($p = 0.83$, 2 tailed paired t -test).

We categorized ‘experience in a quantitative field’ into three groups. The ‘limited experience’ group includes those participants with a minimal exposure to mathematics and statistics at universities or at their final year of high school. These participants typically study humanities subjects at universities. The ‘significant experience’ group includes those participants who have taken numerous subjects in a quantitative field such as mathematics, physics, statistics or engineering. These participants are typically engineering or science majors. The ‘average experience’ group includes those who have studied one or two subjects in a quantitative field and are typically psychology or social science majors. As can be seen in Table 2, there is no evidence that those with more experience in a quantitative field are more likely to solve the nine-dot problem.

three different stimulation conditions (‘L–R+ stimulation’, stimulation of the opposite polarities, that is ‘L+R– stimulation’, and ‘sham stimulation’). As in the current study, participants were given a total of 9 min before, during and after stimulation to solve the problem. We found that three out of seven subjects who failed to solve the nine-dot problem before stimulation became successful as a result of ‘L–R+’ stimulation. In contrast, no one in the L+R– stimulation group (stimulation of the opposite polarities) nor the sham stimulation group could solve the problem before, during or after stimulation. This confirms the findings of Chi and Snyder [6] that only L–R+ stimulation (not L+R– stimulation nor sham stimulation) could improve performance for an insight problem. It also supports the evidence that alertness is unlikely to be a factor, since stimulation of the opposite polarities (L+R– stimulation) did not affect performance.

3. Results

None of the 22 participants in the main experiment solved the nine-dot problem before stimulation. But with 10 min of right lateralizing transcranial direct current stimulation (tDCS), we found that more than 40% of participants could do so. Specifically, whereas none of the 11 participants in the ‘sham stimulation’ control condition solved the nine-dot problem before, during or immediately after stimulation, five (four during stimulation, one immediately after stimulation) out of eleven participants solved the problem as a result of L–R+ stimulation ($p = 0.018$, one tail fisher’s exact test).

The probability of observing this finding by chance is miniscule. Even if we made the overly conservative assumption that the expected solution rate for the nine-dot problem was 5% (instead of 0%, which we observed), the probability that by chance, 5 out of 11 in the L–R+ stimulation group solved the problem is less than one in ten thousand, according to analysis using the binomial distribution.

We can rule out the possibility that an unrepresentative sample explains our results. Table 1 shows that there is no significant difference in demographic characteristics between the two stimulation groups. Table 2 shows that there is no significant difference in demographic characteristics between those people who solved the nine-dot problem and those people who could not.

Table 2
Demographic characteristics of those who solved the 9 dots problem versus those who failed.

	Success	Failure
Age (years)	29.6 ± 4.4	30.2 ± 3.3
Gender (number of males/the total number of participants)	2/5	7/17
Score in the arithmetic control task before stimulation	21.2 ± 4.6	26.4 ± 2.4
Score in the arithmetic control task after stimulation ('Offline')	26 ± 5.7	26.5 ± 3.0
Experience in a quantitative field (number of participants)		
Limited experience	3	7
Average experience	1	6
Significant experience	1	4

Values are presented as mean ± standard error of the mean. Participants across the two stimulation groups did not differ in terms of age ($p=0.92$, 2 tailed independent t -test), gender ($p=1$, 2 tailed fisher's exact test), baseline score in the arithmetic control task ($p=0.31$, 2 tailed independent t -test) or experience in a quantitative field ($p=0.82$, 2 tailed fisher's exact test). There was no significant change in the scores of the arithmetic control task for those who solved the 9 dots problem ($p=0.10$, 2 tailed paired t -test) or for those who failed ($p=0.99$, 2 tailed paired t -test).

We would like to emphasize the robustness of our finding. The finding that tDCS enabled more than 40% of participants to solve the 'unsolvable' nine-dot problem is consistent with our pilot study (see Section 2), which shows that whereas no one solved the nine-dot problem in the sham stimulation condition, 3 out of 7 participants in the L – R+ stimulation condition did so after stimulation. It is also strongly supported by subsequent studies where we, for curiosity, included the nine-dot problem at the end of an unrelated experiment. In fact, of all the data we have ever collected by 2 different experimenters over eight months, we found that 0 out of 29 participants in the sham stimulation condition solved the nine-dots problem, whereas 14 out of 33 participants (naïve to the nine-dot problem) in the L – R+ stimulation condition did so. The probability that by chance 14 out of 33 participants solved the nine-dot problem is less than 1 in a billion, according to analysis using binominal distribution (assuming that the expected solution rate without stimulation is 5%).

3.1. Case report

Intriguingly, the one person in our study who did solve the 9 dots problem without stimulation, was the one who was excluded due to a head injury which occurred at the age of 9 years and 11 months. This information was not revealed by him during our standard phone screening, but rather at the outset of the experiment in our lab. He was immediately excluded from the experiment. However, since he was already at the lab, he expressed an interest in attempting to do the problem we had asked our participants to do. The experimenter agreed out of curiosity. This 'participant' was the only person excluded from our study who attempted the 9 dots problem.

Interestingly, the participant not only was able to solve the 9 dots problem but also the difficult 'matchstick' insight problem presented in an earlier study by Chi and Snyder [6].

The participant was then interviewed about his cognitive style. He revealed that he sees things literally, piece by piece, instead of the big picture:

He said, 'I only focus on a particular thing, so if I walk into a room, I'd just take things methodically, each thing at the time, I don't look at the whole picture. . . I notice everything by itself, as singular objects instead of the whole scene. . . even my writing. . . I'm only focused on one part. . . My long term memory is very very good. . . I can recall everything that happened in year 6 (12 years old).

The experimenter then asked what specific injury he had suffered. He volunteered to send us his medical report from 11 years ago. In the report, his neurologist noted that he had suffered multiple injuries to the left hemisphere, and a "fracture at the left temporal bone". This case report, although not formally a part of our study, is consistent with previous reports that unusual skills in savants are often associated with dysfunction of the left ATL [17,25] and that inhibiting the left ATL by non-invasive brain stimulation can induce such unusual skills in some situations [5,26].

4. Discussion

The nine-dot problem is a subset of problems that, although computationally simple, are nonetheless extremely difficult to solve [16]. Why might this be so?

One view is that our brains, especially the left hemisphere [12], are wired to interpret the world through the filters of past experience [27]. We are inclined to see stars, not as discrete elements, but as constellations with meanings and narratives [26]. Similarly, we are inclined to see the nine-dot as a Gestalt – a square, with imposed rigid boundaries [16]. This mechanism is mostly unconscious [27], and cannot be easily overridden [16]. It allows us to rapidly deal with familiar situations [27] but constrains us from 'thinking outside the box' [6], even after we are explicitly instructed that the solution requires us to do just that [16,33].

But we discovered that an atypical protocol for tDCS enabled people to solve such an inherently difficult problem. We argue that this finding is due to inhibiting networks associated with top down imposition of prior knowledge, knowledge that inclines us to join the dots up within the square. In particular, this is achieved by inhibiting the left anterior temporal lobe, an area that is believed to filter or combine lower-level information into meaningful patterns [2,6]. Or more generally, by diminishing the left hemisphere, the hemisphere that is thought to specialize for recalling or performing previously learned patterns [6,12,13,23]. This view is consistent with earlier reports that inhibiting the left ATL with transcranial magnetic stimulation can mitigate 'magical thinking' [3] and improve numerosity [26], presumably by reducing our predisposition to interpret random dots as meaningful patterns. As Kershaw and Ohlsson [16] argued, there are multiple causes of difficulty in reaching insight. Our finding that tDCS enabled about 40% of participants to solve the previously 'unsolvable' problem is consistent with evidence that up to about 40% of participants can solve the nine-dot problem if they were told that the solution requires going outside the 'square' (Kershaw and Ohlsson [16]).

Importantly, our paradigm for brain stimulation is unlike other attempts for enhancing cognition [8,9,14,31] in that we did not aim to enhance an existing ability by exciting a specific brain region associated with that ability. Instead, our stimulation protocol aims to mirror left hemisphere inhibition together with right hemisphere facilitation, a condition that characterizes some individuals with extraordinary savant like skills [25,29,30].

While there could well be alternative explanations, we would like to emphasize that our results that tDCS enabled over 40% of participants to solve the nine-dot problem stand on their own. The nine-dot problem is so inherently difficult that most people fail to solve the problem even if they are given hints, a long time to solve the problem, or 100 attempts to solve the problem [16,33]. In fact, even amongst those who have been shown the solution, more than one third could not reproduce the solution one week later [33]. People's struggle with solving this problem appears analogous to evidence that cognitive biases are inherently difficult to avoid, even for those people who have been taught to do so [15]. Our findings suggest that our stimulation protocol may be a method of

mitigating some of the cognitive biases discovered by Kahneman et al. [15].

Is it possible to benefit from solving such a difficult problem by non-invasive brain stimulation without incurring costs in other dimensions of cognition [20]? This is beyond the focus of the current study but we believe that the costs from brief stimulation are likely to be minimal and temporary. This view is consistent with analogous evidence that tDCS, by exciting the non-dominant motor area and simultaneously inhibiting the dominant motor area, can differentially enhance the motor skills of the non-dominant hand without noticeably diminishing performance of the dominant hand [4,23,32]. It is also consistent with our finding that L – R+ stimulation differentially enhanced performance on the nine-dots problem but did not affect performance on the arithmetic control task (see Table 1). It would be interesting in further studies to apply brain stimulation in combination with neuroimaging to determine the intricate tradeoffs involved and the optimal stimulation protocol that enables extraordinary performance for a particular task. We conjecture that brain stimulation has more potential for facilitating those tasks that our minds are not well adapted to than those tasks that our minds are optimized for.

In conclusion, the fact that our paradigm of tDCS enables the solution of 9 dot problem leads us to question whether it might also be helpful for dealing with a broader class of tasks that, although deceptively simple, are nonetheless extremely difficult due to our cognitive makeup.

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