Direct current brain stimulation enhances navigation efficiency in individuals with low spatial sense of direction

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The aim of this study was to evaluate the influence of right versus left temporal transcranial direct current stimulation (tDCS) on navigation efficiency and spatial memory in individuals with low versus high spatial skills. A mixed design administered low (0.5 mA) versus high (2.0 mA) anodal tDCS (within-participants) over the right or the left temporal lobe (between-participants), centered at electrode site T8 (right) or T7 (left). During stimulation, participants navigated virtual environments in search of specified landmarks, and data were logged in terms of current position and heading over time. Following stimulation, participants completed pointing and map-drawing spatial memory tests. Individual differences in sense of direction reliably and inversely predicted navigation advantages in the 2.0 versus 0.5 mA right hemisphere stimulation condition ($R^2 = 0.45$, $P < 0.01$); in other words, individuals with lower sense of direction showed increased navigation efficiency in the 2.0 versus 0.5 mA condition. Spatial memory tests also showed the development of relatively comprehensive spatial memories: bidimensional regression indicated lower distortion in sketch maps drawn following 2.0 versus 0.5 mA right temporal lobe stimulation ($F = 8.7$, $P < 0.05$). Data provide the first demonstration that right temporal anodal tDCS may hold potential for enhancing navigation efficiency in otherwise poor navigators. Data support neuroimaging studies showing the engagement of right temporal brain regions in developing and applying spatial memories during complex navigation tasks, and uniquely suggest that continuing research may find value in optimizing stimulation parameters (intensity, focality) as a function of individual differences. *NeuroReport* **25:1175–1179 © 2014 Wolters Kluwer Health | Lippincott Williams & Wilkins.**

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Introduction

As individuals experience environments, they gradually develop knowledge of locations, distances, and directions, and these elements of spatial knowledge ultimately integrate into cohesive mental representations of large-scale spaces [1]. In many cases, these mental representations can become highly detailed and elaborate, affording flexible spatial behavior such as identifying shortcuts, providing wayfinding directions, and circumventing detours [2,3]. Decades of research have identified distinct neural structures deemed responsible for developing and applying such elaborate spatial knowledge, including right temporal brain structures such as the hippocampus and the parahippocampus [4]. For instance, patients with right (but not left) temporal lobectomy show robust spatial learning deficits during virtual navigation [5], functional neuroimaging data show right hippocampal activation during successful virtual navigation through large-scale environments [3], and electroencephalography (EEG) shows dominant activity in right temporal structures while participants develop map-like memories during virtual navigation [6]. Thus, considerable evidence points to diverse right temporal lobe involvement in developing memory representations affording flexible spatial problem solving during navigation. The present research asks whether low-current stimulation of right versus left temporal regions of the human cerebral cortex might enhance such spatial processes by facilitating neuronal excitability in regions responsible for supporting navigation performance.

Transcranial direct current stimulation (tDCS) involves the noninvasive administration of low direct current flow through the cerebral cortex by electrodes positioned on the scalp. Current can be administered by anodal or cathodal polarity, with anodal enhancing and cathodal reducing cortical excitability through shifts in neuronal resting membrane potential [7]. Over the past few decades, tDCS has gained considerable popularity in the cognitive, rehabilitative, and clinical domains, and reviews and meta-analyses suggest that anodal stimulation over a range of cortical areas reliably induces performance advantages on several cognitive processes [8,9], even when cathodal does not [10,11]. For instance, Fregni *et al.* [10] found that 1 mA of anodal tDCS over the left prefrontal cortex increases accuracy during a verbal working memory task, and 2 mA of anodal tDCS over parietal regions can enhance certain aspects of visual

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attention [12]. Relatively few studies, however, have investigated tDCS over temporal regions. For instance, Boggio *et al.* [13] reported that 2 mA left temporal anodal stimulation can induce visual recognition memory enhancements and reduce false memories, and 2 mA right temporal anodal stimulation can improve proper name recall [14]. No research, however, has investigated the effect of temporal lobe stimulation on spatial learning and memory. Furthermore, no studies have investigated whether any domain-specific performance enhancements afforded by low-current brain stimulation may vary as a function of individual differences in spatial skills.

To provide a first examination of these topics, we administered varied current intensity tDCS over the right versus left temporal cortex and examined influences on both online navigation performance and offline spatial memory. Given that individual differences in spatial skills including mental rotation, visualization, perspective-taking, and sense of direction ability predict performance across a range of real-world spatial tasks [15,16], we also examined whether such differences might also predict the utility of brain stimulation in imparting navigation performance advantages. Given research showing the reliable involvement of right temporal lobe regions in acquiring and retrieving spatial knowledge [3,4,6], and research suggesting that anodal tDCS can induce neural membrane depolarization and excitation leading to cognitive performance enhancements [8], we formulated three hypotheses. First, we expected that 2 versus 0.5 mA intensity tDCS over the right, but not left, temporal lobe would produce online navigation advantages in the form of increased path efficiency (decreased turning errors, more direct paths). Second, we expected that these online navigation advantages would not be at the expense of forming comprehensive spatial memories of the navigated environment; specifically, we expected either maintained or enhanced spatial memory following 2 versus 0.5 mA stimulation. Finally, we expected that individuals with relatively low spatial abilities, for instance those with a low sense of direction, might show more evidence for stimulation-induced performance enhancement on online and offline measures.

Materials and methods

Participants and design

Thirty-two healthy male (16 per right/left hemisphere; $M_{age} = 20.1$) students at Tufts University participated for monetary compensation ($60USD); males were selectively sampled to reduce variability in video game experience. Participants self-reported no history of seizures, head or brain injury, neurosurgery, neurological or psychiatric disorders, sensitive scalp, or adverse reactions to prior tDCS. All participants provided written informed consent, and the study was approved by the institutional review board at Tufts University and the Army Human Research Protections Office, and carried out in accordance with the Declaration of Helsinki. We manipulated tDCS intensity across two levels (0.5 and 2.0 mA) in a within-participant design and hemisphere of stimulation (right, left) in a between-participant design. Traditional sham (ramp up then cutoff after 30 s) procedures were not chosen, given ongoing experiments in our laboratory showing that participants distinguish sham (but not 0.5 mA) versus active (2.0 mA) current with high accuracy, compromising participant blinding, and possibly introducing unintended demand characteristics into within-participant designs. To our knowledge, no research to date suggests that such a low-intensity current can reliably influence any aspect of cognitive performance relative to a sham procedure [8].

Individual difference instruments

We used a card rotation task to assess spatial relations ability [accuracy and reaction time (RT)], the perspective-taking test to assess the ability to adopt body-referenced perspectives while viewing a map (accuracy and RT) [17], the video game experience questionnaire to assess frequency and ability of video gaming (composite scored) [18], and the Santa Barbara Sense of Direction scale to assess general environmental spatial ability (composite scored) [19].

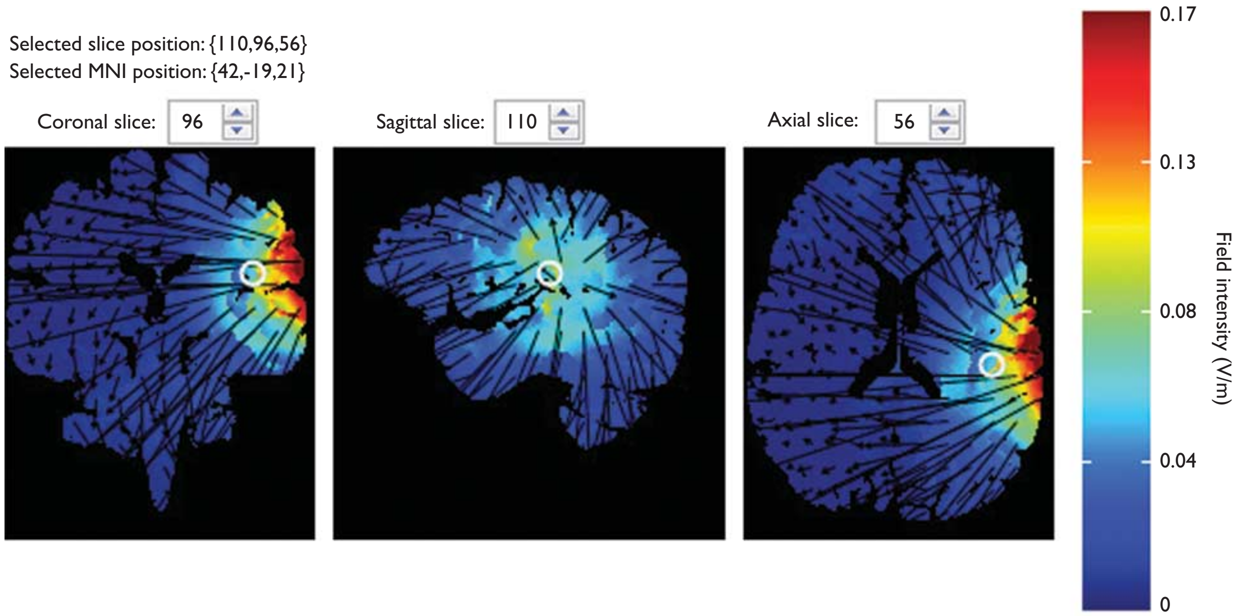
Navigation task

We used a navigation task well validated for its reliability and sensitivity [20]. The task involves navigating through large-scale virtual towns in an attempt to locate a sequence of 10 landmark objectives, receiving instructions on-screen (e.g. *You have reached the Bank. Proceed to the Library.*). Three unique virtual environments were used (one for practice, then one for each of the two sessions), each similar in size (~70 000 m^2), landmark density, and complexity.

Transcranial direct current stimulation administration

We used a targeted ring 4×1 electrode high-definition tDCS system manufactured by Soterix Medical Inc. (New York, New York, USA) that allows double-blind administration of preprogrammed current intensities. The ring electrode montage allows for higher spatial focality relative to traditional rectangular pads [21]. In this study, we delivered anodal current by placing four cathodal electrodes in a ring around a single center anodal electrode, on a 74-channel EasyCap EEG cap (EasyCap GmbH, Herrsching, Germany) sized to each participant. The center electrode was positioned centered on the centrotemporal cortex at T8 (right) or T7 (left), and the ring electrodes at CP6, FC6, FT10, and TP10 (right) or CP5, FC5, FT9, and TP9 (left), according to the international 10/20 EEG system. Montage-specific field intensities were modeled using the HDExplore software (Soterix Medical Inc.) to confirm temporal lobe (approximated in Fig. 1) current propagation [22]. Electrodes were enclosed in plastic holders that positioned Ag/AgCl

Fig. 1



Approximated direct current propagation through the right temporal cortex at 2.0 mA intensity.

sintered ring electrodes ~7 mm above the scalp; Signa gel (Parker Laboratories, Fairfield, New Jersey, USA) was used to conduct current between the ring electrode and the surface of the scalp. Impedances were reduced below 2 kΩ by parting hair, cleaning scalp sites with alcohol, and/or introducing additional gel.

Memory tests

Two spatial memory tests were used. A pointing task was embedded within the navigated virtual environment and involved pointing in the direction of specified landmarks, allowing us to test memory for relative landmark positions. We measured the absolute angular offset between the indicated and the actual landmark direction. The map-drawing task involved producing a sketch map of the navigated environment on a blank piece of paper; maps were analyzed using bidimensional regression to evaluate the sketch map's overall layout relative to the actual environment.

Procedure

Participants visited the laboratory on three separate occasions, each at least 24 h apart and at the same time of day. During the first session, they completed questionnaires, practice navigation and spatial memory tests, without tDCS. During the second and third sessions, participants completed the navigation task while receiving either 0.5 or 2.0 mA tDCS in a counterbalanced order across participants. At the beginning of each session, a brief practice navigation task involved five successive navigation trials through an open virtual environment containing multiple ordinary objects (e.g. traffic light, tree); this task took ~30 s, allowing ramp up of stimulation to the target intensity before beginning the primary navigation task. Constant current tDCS was administered at 0.5 or 2.0 mA for the duration of navigation (up to 20 min total). During navigation, participants were placed into one of the two virtual environments and asked to navigate between the 10 successive origin–destination pairs.

During tDCS sessions, participants used a perceived sensation scale to rate discomfort on a standard scale from 0 (*Cold*) to 9 (*Hurts a Lot*); ratings were requested at tDCS onset (before practice), immediately before navigation, immediately upon concluding navigation, and 5 min after tDCS cessation. Following navigation, participants waited during a 5-min retention interval and then completed a series of two spatial memory tests in a counterbalanced order: pointing and map drawing. Pointing was self-paced through 32 randomly ordered trials, during which participants were placed in a randomly selected location in the virtual environment and asked to point to a single nonvisible landmark. Participants were allowed up to 5 min to draw the sketch map.

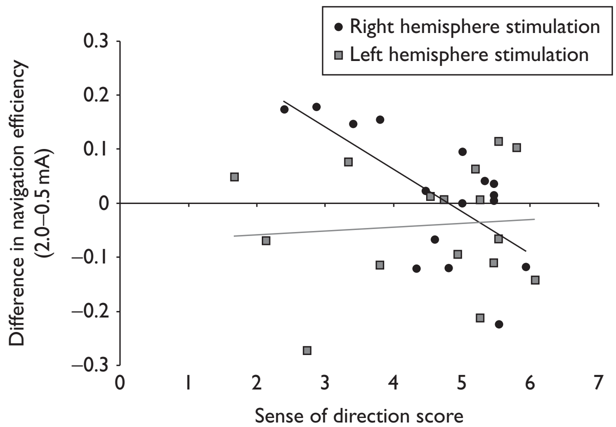
Results

Right hemisphere stimulation

Navigation performance

An omnibus 2 (stimulation: 0.5, 2.0 mA) × 10 (trial number) analysis of variance (ANOVA) with six covariates derived from individual differences questionnaires showed an interaction between stimulation and the sense

Fig. 2



Linear relationship between sense of direction and navigation efficiency advantages imparted by 2.0 versus 0.5 mA stimulation for left (gray squares) and right (black circles) hemisphere stimulation.

of direction covariate [$F(1, 9) = 6.0$, $P < 0.05$, $\eta^2 = 0.01$]. There was also an interaction between trial number and the perspective-taking (RTs) covariate [$F(9, 81) = 2.45$, $P < 0.05$, $\eta^2 = 0.06$]. To examine the first effect, we performed a linear regression, showing that sense of direction scores negatively predicted overall path efficiency in the 2.0 versus 0.5 mA condition (i.e. 2.0 – 0.5 mA difference score) [$F(1, 15) = 11.44$, $P < 0.01$, $R^2 = 0.45$, $\beta_{std} = -0.671$]. In other words, higher current intensity only elicited stimulation-induced navigation performance gains in individuals with a lower sense of direction (Fig. 2). A median split based on sense of direction showed lower path efficiency in low versus high sense of direction individuals at 0.5 mA stimulation ($M_{lowSOD} = 0.54$, $M_{highSOD} = 0.60$), but this difference was mitigated with 2.0 mA stimulation ($M_{lowSOD} = 0.59$, $M_{highSOD} = 0.58$).

To examine the second interaction, we performed a linear regression, testing whether perspective-taking RTs would predict the slope of performance gains over the course of the 10 trials; the regression showed that individuals with longer RTs on the perspective-taking test also tended to show lower performance increases over the course of the 10 trials, although this pattern did not reach significance [$F(1, 15) = 1.86$, $P = 0.19$, $R^2 = 0.12$, $\beta_{std} = -0.34$].

Spatial memory performance

For the pointing task, a single-factor (stimulation: 0.5, 2.0 mA) ANOVA with the six individual difference covariates showed no significant effects ($P_{min} = 0.37$). For the map-drawing task, we tested for differences in distortion index derived from bidimensional regression; analysis showed a main effect of stimulation, with lower map distortion following 2.0 ($M = 75.7$) versus 0.5 mA ($M = 78.0$) stimulation [$F(1, 9) = 8.7$, $P < 0.05$, $\eta^2 = 0.06$]. Note that the overall number of landmarks recalled (drawn) did not differ between stimulation conditions.

Left hemisphere stimulation

Navigation performance

An omnibus 2 (stimulation: 0.5, 2.0 mA) × 10 (trial number) ANOVA with the six covariates showed no significant effects ($P_{min} = 0.15$).

Spatial memory performance

For the pointing task, a single-factor 2 (stimulation: 0.5, 2.0 mA) ANOVA with the six covariates showed no significant effects ($P_{min} = 0.47$). For the map-drawing task, analysis again showed no significant effects ($P_{min} = 0.12$).

Discussion

The present study examined whether anodal tDCS administered over right or left temporal regions influences online measures of navigation efficiency and offline measures of spatial memory. We hypothesized that excitatory stimulation of the right temporal brain structures implicated in spatial memory development during large-scale virtual navigation would enhance navigation efficiency and spatial memory for the navigated environment. This hypothesis was borne out, but navigation efficiency advantages were only observed with individuals with a relatively low sense of direction. There was also some evidence that right temporal stimulation increases the overall configural accuracy of spatial memory assessed by sketch map analysis; this effect was small ($\eta^2 = 0.06$) and was only found in nine of the 16 participants.

Sense of direction refers to the ability to discriminate environmental cues, memorize locations into a map-like structure, use effective route learning strategies, and align and update self-to-object relations during wayfinding [19,23]. Sense of direction thus measures a range of mental processes critical for supporting wayfinding, and tends to predict real-world behavior more strongly than relatively small-scale spatial processes such as visualization, mental rotation, or perspective taking [16]. The present data show that low-current stimulation of the right temporal region can selectively enhance navigation efficiency among individuals with a relatively low sense of direction; there is also evidence (Fig. 2) that some individuals with a relatively high sense of direction showed stimulation-induced efficiency decreases.

Brain stimulation in individuals with a low sense of direction may result in reduced excitatory thresholds in neural networks responsible for acquiring spatial knowledge during navigation, enhancing otherwise suboptimal performance by facilitating task-relevant temporal lobe activation. It could be the case that activating these brain regions promotes spatial learning strategies focused on relatively allocentric (world-centered, configural) aspects of the environment, a strategy typically adopted by individuals with a relatively high sense of direction [24, 25]. Invoking allocentric memory strategies may explain how 2.0 mA of stimulation brought the online navigation performance of individuals with a low sense of direction up to the level of those with a high sense of direction. Some individuals with a particularly high sense of direction showed relatively poor performance with 2.0 mA stimulation; extant research suggests that individuals with a high sense of direction tend to activate brain networks including medial temporal, inferior parietal, and thalamic areas [24], believed to underlie the flexible development and use of allocentric representations that can support highly efficient navigation. Stimulating otherwise optimized neural networks may induce sub-optimal efficiency in these individuals. Of course, some of these areas, particularly relatively medial ones, may be difficult to target by tDCS without inadvertently influencing brain activity in neighboring regions; more advanced modeling of current flow may increase the feasibility of deep focal targeting of hippocampal structures in the near future [22].

Conclusion

We provide the first demonstration that right temporal anodal tDCS may hold potential for enhancing navigation efficiency in otherwise poor navigators. To our knowledge, this is the first demonstration that under specific circumstances, tDCS may not prove a one-size-fits-all solution for enhancing performance, and continuing research may find value in targeting stimulation parameters (intensity, focality) to individual difference variations. Of course, the nature and value of these individual differences may vary as a function of specific task demands and stimulation procedures. This finding extends the recent literature and motivates continuing research into understanding the potentially complex effects of tDCS across a range of individuals, task demands, and stimulation parameters.

Acknowledgements

Conflicts of interest

There are no conflicts of interest.

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