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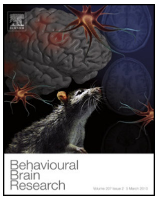

Research report

Prefrontal transcranial direct current stimulation improves fundamental vehicle control abilities

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HIGHLIGHTS

- tDCS was applied to the prefrontal cortex bilaterally in a simulated driving task.
- Up-regulation of the right prefrontal cortex improved vehicle control abilities.
- tDCS can be a tool to examine brain functioning in everyday life situations.

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ABSTRACT

Noninvasive brain stimulation techniques have increasingly attracted the attention of neuroscientists because they enable the identification of the causal role of a targeted brain region. However, few studies have applied such techniques to everyday life situations. Here, we investigate the causal role of the dorsolateral prefrontal cortex (DLPFC) in fundamental vehicle control abilities. Thirteen participants underwent a simulated driving task under prefrontal transcranial direct current stimulation (tDCS) on three separate testing days. Each testing day was randomly assigned to either anodal over the right with cathodal over the left DLPFC, cathodal over the right with anodal over the left DLPFC, or sham stimulation. The driving task required the participants to maintain an inter-vehicle distance to a leading car traveling a winding road with a constant speed. Driving performance was quantified using two metrics: the root-mean-square error of inter-vehicle distance as car-following performance, and the standard deviation of lateral position as lane-keeping performance. Results showed that both car-following and lane-keeping performances were significantly greater for right anodal/left cathodal compared with right cathodal/left cathodal and sham stimulation. These results suggest not only the causal involvement of the DLPFC in driving, but also right hemisphere dominance for vehicle control. The findings of this study indicate that tDCS can be a useful tool to examine the causal role of a specific brain region in ecologically valid environments, and also might be a help to drivers with difficulties in vehicle control.

1. Introduction

Recently, non-invasive brain stimulation techniques have increasingly attracted attention as a tool for the exploration of the causal roles of a targeted brain region. Among such techniques, transcranial direct current stimulation (tDCS) is particularly portable and therefore feasible to identify brain functions in everyday life situations [1]. However, there are still few studies that have applied tDCS to such ecologically valid environments.

Driving is a day-to-day activity that engages multiple cognitive processes. For safe driving, for instance, drivers must continually pay attention to the traffic environment, acquire and interpret relevant information, and select and execute appropriate actions under traffic law. Even when driving on an empty road, drivers have to control vehicle speed and lateral position in a lane and maintain readiness for handling abrupt disturbances, such as gusty winds or wheel tracks. Thus, driving is considered to be a good exemplar for tDCS studies in everyday life situations where multiple cognitive (and therefore multiple brain) functions are entangled in a complex fashion. Additionally, elucidating neural mechanisms underlying

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vehicle driving is expected to add new insights for the design of transportation safety systems.

To our knowledge, Beeli et al. [2] provided the first and only study in this context. They examined the impact of tDCS application over the dorsolateral prefrontal cortex (DLPFC) on risk-aversive driving behavior in a simulated driving environment, and found less risky driving tendency after anodal compared with cathodal tDCS. This aspect of their findings is consistent with earlier noninvasive brain stimulation studies demonstrating the involvement of the DLPFC in risk-aversive decision-making [3–7]. However, they found no evidence of the right hemisphere dominance in risk-aversive decision-making demonstrated by most of those earlier studies. This discrepancy might highlight the difficulty of extrapolating results from the well-controlled laboratory to ecologically valid environments.

Although the previous study by Beeli et al. [2] found a causal role of the DLPFC in driving, it is well known that the DLPFC is associated with cognitive functions of various kinds. The right DLPFC, for instance, plays a critical role in sustained attention [8–10], orienting of attention [11], error processing [12,13], planning [14], and proactive response inhibition [15]. Moreover, it is also evident that these cognitive abilities are imperative for safe driving [16]. Therefore, modulating DLPFC activity with tDCS can be expected to affect various aspects of driving.

According to previous neuroimaging studies, however, the involvement of the DLPFC in vehicle driving remains controversial. Uchiyama et al. [17] have shown that the right DLPFC is distinctively activated in a simulated driving task in which maintaining an inter-vehicle distance to a leading car is required. Just et al. [18] have demonstrated the activation of the left, but not right, DLFPC while driving on a rural road with no other road users. Additionally, Spiers and Maguire [19] revealed that right DLPFC activity increases when drivers consider road traffic rules during free navigation in a simulated traffic environment. However, other driving neuroimaging studies did not find any significant activation in the DLPFC [20–27].

Thus, we here investigate the causal role of the DLPFC in fundamental vehicle control abilities. More specifically, the impacts of bilateral prefrontal tDCS application on car-following and lane-keeping performances were evaluated in a simulated driving environment. For tDCS, two (anodal and cathodal) electrodes, having opposite effects in terms of cortical excitability, are spatially arranged in accordance with the research aims. For anodal stimulation to a target brain region, for instance, a cathodal electrode is often placed on the mastoid or the arm to avoid (or mitigate) nuisance effects of cathodal stimulation on non-targeted brain regions. In the present study, electrodes are placed over the left and right DLPFC, respectively. This electrode placement is expected to facilitate the lateralization of the DLPFC, therefore enabling us not only to assess the causal involvement of the DLPFC in driving but also to investigate functional DLPFC lateralization for vehicle control.

2. Materials and methods

2.1. Ethics statement

The study was approved by the institutional ethics committee of Toyota Central R&D Laboratories, Inc., which conforms to the Declaration of Helsinki. All participants gave their written informed consent to participate in this study.

2.2. Participants

Thirteen adults (11 males and 2 females, mean age of 35 ± 6 years) participated in this study. All participants had normal or corrected-to-normal vision, were right-handed according to the Edinburgh Handedness Inventory [28], and were free from serious medical conditions. Each had at least four years of experience as a licensed driver. Self-reported annual driving distances were 3000–15,000 km (median = 8000 km).

2.3. Driving task

We employed a homemade driving simulator that runs on an IBM compatible personal computer [17,26]. Traffic scenes from a driver's point of view (Fig. 1A) were generated and displayed on a 60 in. screen using an LCD projector (ELP-730, EPSON, Suwa, Japan) with a vertical refresh rate of 60 Hz and a spatial resolution of 1024 by 768 pixels. A car seat was located approximately 160 cm in front of the screen, with a steering wheel and accelerator and brake pedals (Driving Force GT, Logitech, Tokyo, Japan). Any auditory stimulation, such as the sound of the engine exhaust, was not provided. Driving data were recorded with a sampling rate of 50 Hz.

The driving task was to follow a leading car traveling on a driving lane on a slightly winding road for 13 min (Fig. 1B). Ten seconds after the task was activated, the leading car started to gradually accelerate to 100 km/h. Participants were required to remember the initial inter-vehicle distance (60 m) and to maintain it throughout the task by operating the steering wheel and the two pedals.

2.4. Brain stimulation

Brain stimulation was non-invasively delivered using a battery-driven constant current stimulator (DC-Stimulator Plus, neuroConn GmbH, Ilmenau, Germany) through a pair of saline-soaked surface sponge electrodes (5 by 7 cm). To stimulate the left and right DLPFC, the electrodes were respectively placed over the F3 and F4 positions in accordance with the international EEG 10/20 system [29]. For the purpose of comparison, three stimulation conditions were employed: (1) F4 anodal with F3 cathodal stimulation (RA/LC), (2) F3 anodal with F4 cathodal stimulation (RC/LA), and (3) sham stimulation. In the RA/LC and RC/LA conditions, stimulation was applied for 20 min with a constant direct current intensity of 1.5 mA, linearly ramping up and down over 30 s; while in the sham condition, although the electrode montage and the current intensity were identical to those in the RA/LC condition, the stimulation duration was shortened to 30 s (Fig. 1C).

2.5. Procedure

Each participant repeatedly performed the driving task on three separate testing days with an interval of at least a week between them. Testing days were randomly assigned to the RA/LC, RC/LA or sham conditions; participants were blind to the conditions. In each testing day, participants were gave an opportunity to practice the task for a few minutes. Then, tDCS began to be delivered to the participants. Five minutes afterwards, they reported their self-evaluated current sleepiness using a Japanese version [30] of the Karolinska Sleepiness Scale (KSS: 0 = extremely alert, 2 = alert, 4 = neither alert nor sleepy, 6 = sleepy, 8 = very sleepy, fighting with sleep) [31], and then completed the driving task. Immediately after the driving task was completed, subjective sleepiness was again assessed using the KSS.

2.6. Data analysis

In the present study, car-following and lane-keeping performances were evaluated as fundamental vehicle control abilities for each participant and each stimulation condition. Car-following performance was quantified with the root-mean-square error of