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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

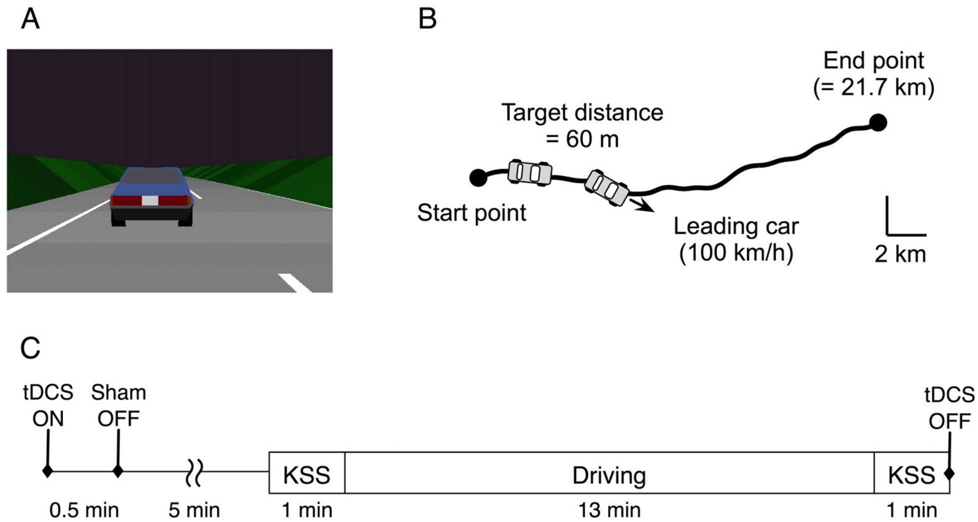

Fig. 1. Experimental procedures. The present study employed a homemade driving simulator (A). Participants were instructed to maintain the inter-vehicle distance to a leading car traveling in a driving lane with a constant speed (B) during transcranial direct current stimulation over the bilateral prefrontal cortex (C). Additionally, subjective sleepiness was recorded immediately before and after the driving task using the Karolinska Sleepiness Scale (KSS).

inter-vehicle distance to the leading car, while lane-keeping performance was indexed by the standard deviation of the lateral position of the controlled vehicle. In this regard, driving data in the first minute were discarded from the computation of these performance metrics to exclude the initial transient period. Moreover, several lines of evidence suggest that driving performance in monotonous environments deteriorates with time on task due to increased sleepiness and/or fatigue [31–33]. To examine such time-on-task effects in addition to tDCS effects, performance metrics were calculated for each four min epoch (Early: 1–5 min; Middle: 5–9 min; Late: 9–13 min). Finally, for each performance metric as a dependent variable, a two-way repeated measures analysis of variance (ANOVA) with the Greenhouse–Geisser correction for sphericity was performed, with three levels of stimulation conditions (RA/LC, RC/LA and sham) and three levels of time epochs (Early, Middle and Late). In this analysis, subject was treated as a fixed effect to allow large inter-individual variability in tDCS effects due, for example, to inter-individual variability in the laterality of brain activity [34]. When it was appropriate, post hoc comparisons were further conducted using Scheffe's multiple comparison test. Additionally, we also performed an ANOVA on subjective sleepiness assessed with the KSS, with three levels of stimulus conditions and two levels of time points (pre- and post-driving task). Statistical significance was set at $P < 0.05$ for all tests.

3. Results

All participants completed the driving task in three testing days. Most of them reported tingly and/or itchy sensations at the beginning of tDCS delivery, which typically faded away after a few minutes.

Fig. 2 shows a typical example of driving data recorded from one participant. Inter-vehicle distance tended to be larger in the initial period due to the abrupt acceleration of the leading car. Even after catching up the leading car (typically less than 1 min later), inter-vehicle distance and lateral position varied with time. Relatively slow and large variability in inter-vehicle distance compared with lateral position data were due to slower vehicle dynamics in response to pedal compared with steering operations. Moreover, traffic lane lines could be always used as a visual cue for lane keeping; in contrast, the initial inter-vehicle distance that was remembered at the beginning of the task was an imagery target for car following. Such differences in control strategy were also a possible source of the variability difference between lateral position and inter-vehicle distance data.

On car-following performance (Fig. 3A), an ANOVA revealed a significant main effect of stimulus condition ($F(1.7, 37) = 7.37$, $P = 0.0031$), but no significant effect of time epoch ($F(1.4, 37) = 1.68$, $P = 0.20$) and no significant interaction between stimulus condition and time epoch ($F(3.1, 37) = 1.99$, $P = 0.13$). According to a post hoc test, car-following performance in the RA/LC condition was significantly better than those in the RC/LA and sham conditions ($P < 0.05$; Fig. 3B). For lane-keeping performance (Fig. 3C), we found a significant main effect of stimulus condition ($F(1.4, 21) = 6.35$, $P = 0.013$), a marginally significant main effect of time epoch ($F(1.1, 21) = 3.38$, $P = 0.075$) and no significant interaction between them ($F(1.8, 21) = 0.56$, $P = 0.69$). Post hoc tests revealed better lane-keeping performance in the RA/LC compared with the RC/LA and sham conditions ($P < 0.05$; Fig. 3D).

Meanwhile, for subjective sleepiness (Fig. 4), an ANOVA found a significant main effect of time point (Pre < Post; $F(1, 24) = 22.93$, $P < 0.001$), but no significant main effect of stimulus condition ($F(2, 24) = 1.71$, $P = 0.20$). No significant interaction was found between time point and stimulus condition ($F(2, 24) = 0.82$, $P = 0.45$).

4. Discussion

The present data showed that both car-following and lane-keeping performances were significantly better in the RA/LC condition compared with the RC/LA and sham conditions. These results demonstrate that up-regulation of the right DLPFC alongside down-regulation of the left DLPFC improves fundamental vehicle control abilities. Our data also showed time-on-task effects. That is, subjective arousal level decreased and lane-keeping performance somewhat deteriorated with time on task. By contrast, there was no distinctive impact of tDCS on subjective sleepiness and no significant interaction of time and stimulus conditions on measured driving performance. These results suggest that bilateral prefrontal tDCS does not mitigate time-on-task effects, such as fatigue or reduced arousal level.

Our findings suggest right DLPFC dominance for vehicle control. This result is consistent with recent functional magnetic resonance (fMRI) evidence from Uchiyama et al. [17] showing the involvement of the right, but not the left, DLPFC in a car-following driving task.

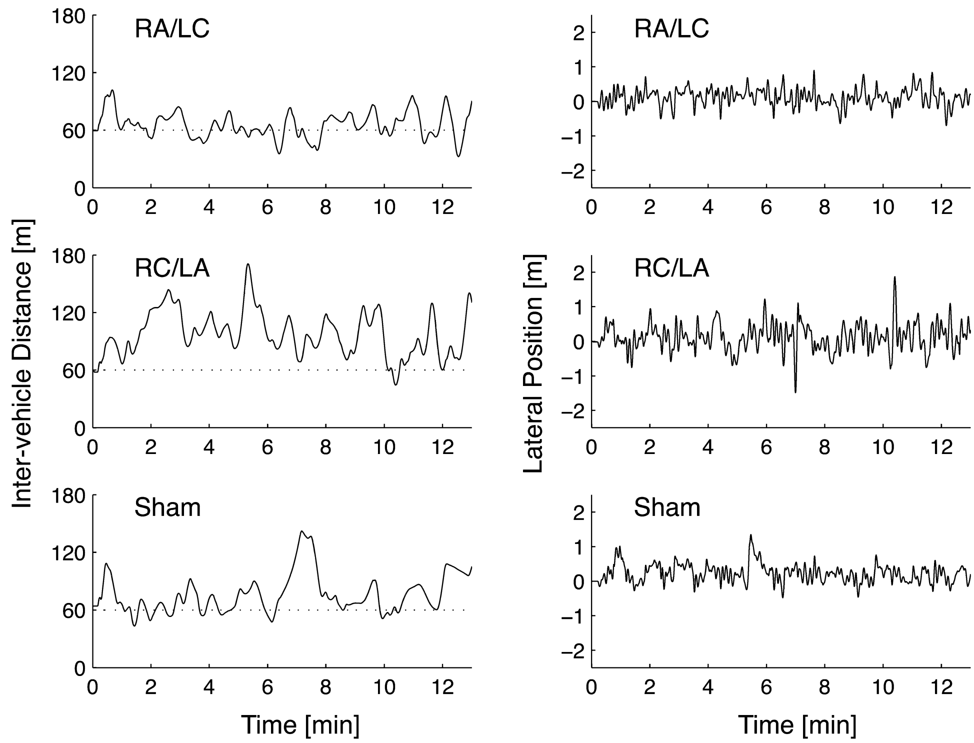

Fig. 2. Examples of driving data. Left and right panels show inter-vehicle distance and lateral position, respectively. Car-following performance was quantified as the root-mean-square error of inter-vehicle distance (target distance = 60 m; dotted lines), whereas lane-keeping performance was measured as the standard deviation of lateral position. Stimulus conditions were either anodal over the right with cathodal over the left dorsolateral prefrontal cortex (RA/LC), cathodal over the right with anodal over the left dorsolateral prefrontal cortex (RC/LA), or sham stimulation.

However, such driving-related activation in the right DLPFC has not been found in most previous neuroimaging studies concerning brain regions associated with driving [20–27]. A possible explanation for this discrepancy is based on differences in attentional demands for carrying out a driving task. The study by Uchiyama et al. [17] and our study required participants to continuously maintain an inter-vehicle distance, whereas other studies required driving a car as usual, mostly in the absence of any traffic. Hence, it is likely that the demanded levels of sustained attention to a driving task are different between these two lines of research. Thus, we can interpret the current data as indicating that the right DLPFC plays a causal role in sustained attention, and therefore in fundamental vehicle control abilities that are underpinned with sustained attention. This interpretation is consistent with a previous low-resolution electric tomography study [35] that has shown more alpha-band related activity (i.e., less neuronal activation) in the right DLPFC during recklessly fast compared with careful driving. Our interpretation is also consistent with several lines of evidence showing right DLPFC dominance for sustained attention. Early neuroimaging studies demonstrated the involvement of the right DLFPC in sustained attention [8–10]. More recently, Coffman et al. [36] have shown that anodal tDCS to the right DLPFC results in improved alerting, but not orienting and executive, attention. Furthermore, we recently demonstrated that spontaneously reduced activity in the right DLPFC during a monotonous cognitive task is a neural signature of effortless automated responding [15]. In contrast, a recent tDCS study with identical electrode placement to that used in the present study has demonstrated that performance in a vigilance task is relatively better in the RC/LA compared with the RA/LC condition. This appears to be inconsistent not only with the current data but also with previously published data showing right DLPFC dominance for sustained attention. However, performance improvement in a vigilance task cannot always be attributed to improved sustained attention. Indeed, the authors suggest that differences in performance improvement between stimulation polarities can be explained by left hemisphere dominance for local discrimination processing of visual stimuli [37–39], rather than by right hemisphere dominance for sustained attention.

Meanwhile, such an interpretation, that anodal tDCS to the right DLPFC improves sustained attention, might appear to contradict our result that prefrontal tDCS had no distinctive effect on arousal level (assessed as subjective sleepiness). However, it should be noted that sustained attention and intrinsic arousal are mutually independent concepts. More specifically, arousal level is a conceptual measure of available attentional resources, whereas sustained attention is a psychological construct that describes a cognitive ability for maintaining the allocation of available attentional resources to achieve a goal over a prolonged period. In this context, sustained attention can vary independently of intrinsic arousal. Therefore, it is possible that anodal tDCS to the right DLPFC has a positive effect on sustained attention, even in situations where arousal level decreases with time on task.

Our results also seem to contradict results by Just et al. [18] demonstrating the involvement of the left, but not the right, DLPFC in driving using a lane-keeping task. Moreover, although Uchiyama et al. [26] used a car-following task similar to that used in Uchiyama et al. [17], they found no significant activation in the right DLPFC while driving. This result also seems to be inconsistent with our interpretation of the current data. However, it might be hard to obtain a coherent explanation for these discrepancies, because experimental conditions are extensively different to each other among those studies, a common issue in existing studies investigating brain regions associated with driving. Observed driving-related activation patterns are considerably different across studies, and not just for the DLPFC. As mentioned above, the primary factor may be task differences. Additionally, various factors such as control conditions (fixation or passive viewing of traffic scenes), simulated traffic environments (rural or urban areas) and input devices

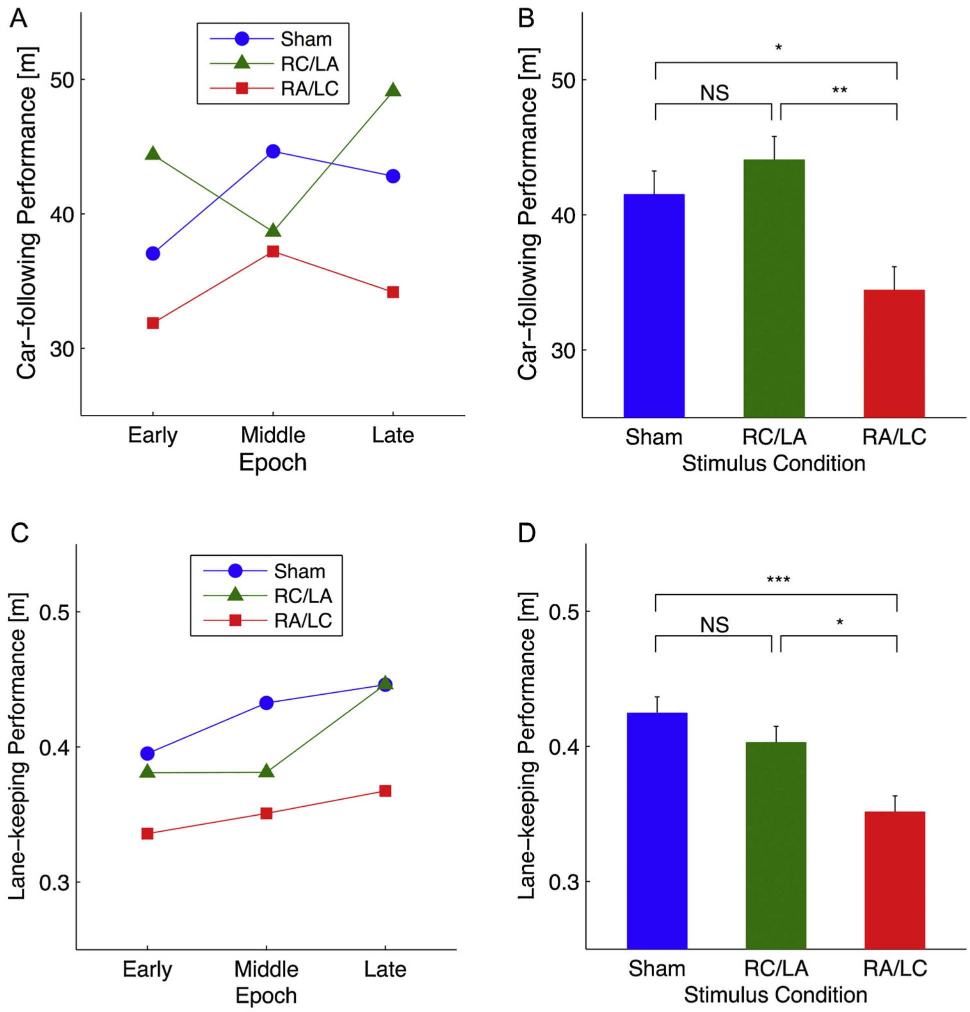

Fig. 3. Impacts of transcranial direct current stimulation over the bilateral dorsolateral prefrontal cortex on fundamental vehicle control abilities. Car-following (A, B) and lane-keeping (C, D) performances were respectively averaged across the 13 participants. RA/LC and RC/LA denotes anodal over the right with cathodal over the left dorsolateral prefrontal cortex and cathodal over the right with anodal over the left dorsolateral prefrontal cortex stimulus conditions, respectively. Error bars represent 95% confidence interval for Scheffe's multiple comparison test. Single, double and triple asterisks represent statistically significant differences (*$P<0.05$; **$P<0.01$; ***$P<0.001$). NS denotes no significance.

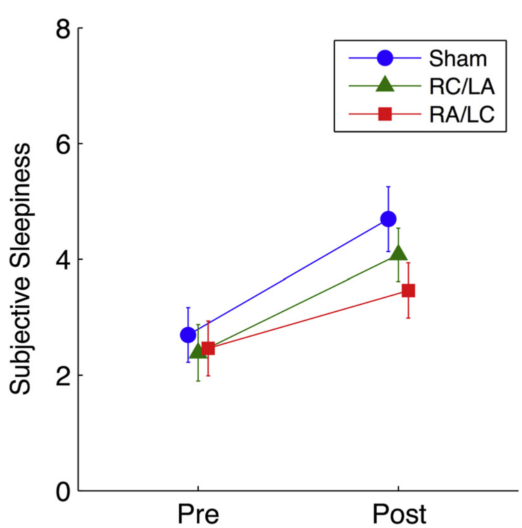

Fig. 4. Impacts of transcranial direct current stimulation over the bilateral prefrontal cortex on subjective sleepiness assessed with the Karolinska Sleepiness Scale. RA/LC and RC/LA denotes anodal over the right with cathodal over the left dorsolateral prefrontal cortex and cathodal over the right with anodal over the left dorsolateral prefrontal cortex stimulus conditions, respectively. Error bars represent the standard error of the mean.

(buttons, joysticks or steering wheel and pedals) could also contribute to differences in brain activation patterns. Such an extensive variety in experimental conditions makes it difficult to directly compare results from different research groups and to identify a key factor generating discrepancies.

The impact of task difficulty on hemispheric lateralization in the prefrontal cortex might also explain the current data demonstrating right DLFPC dominance for vehicle control. Helton et al. [40], for instance, have shown in a functional near infrared spectroscopy study that right hemisphere dominance disappears as task difficulty increases. More recently, Kim et al. [41] have shown that activation pattern in the DLPFC during the observation of driving video clips changes from right-lateralized to bilateral as vehicle speed increases. These lines of evidence strongly imply that the difficulty of the present fundamental driving task is not enough to engage the DLPFC bilaterally and, therefore, that anodal tDCS over the right compared with the left DLPFC provides prominent performance improvement.

Limitations of the present study mainly come from the disadvantages of tDCS. First, the effect of tDCS application might not extend only to the DLPFC. According to a simulation study performed by Neuling et al. [42], bilateral prefrontal tDCS through electrodes placed over F3 and F4 stimulates not only the DLPFC but also the medial prefrontal cortex and the frontal pole. We cannot exclude the possibility of these spillover effects to other brain regions on driving performance. Second, the present statistical analysis treated subject as a fixed effect to allow large inter-individual variability in tDCS effects. Therefore, the generality of our conclusion is to some extent limited. To overcome this problem, stimulus conditions such as electrode loci and current intensity need to be adjusted based on individual structural brain characteristics. Additionally, we should emphasize that the current data were obtained in a simulated driving task. Although improved driving performance by prefrontal tDCS was statistically significant, there is room to argue its practical significance. In particular, the observed slight improvement in lane-keeping performance (less than 0.1 m in terms of the standard deviation of lateral position) might seem operationally meaningless in actual traffic situations. In the present study, however, the simulated driving course contained only gentle curves (radius > 1000 m); such a course layout might be less sensitive to a change in lane-keeping ability. We need further investigation in a situation where accurate and fast steering maneuvers are continuously required.

5. Conclusions

The present study demonstrates that up-regulation of the right DLPFC alongside down-regulation of the left DLPFC improves fundamental vehicle control abilities, which might be attributed to a causal role of the right lateralized DLPFC in sustained attention. The implication of the present findings for road safety is that bilateral prefrontal tDCS could be a help to drivers in situations where there is difficulty in sustained attention, such as monotonous or distractive driving. Nonetheless, further simulation-based studies are needed before conducting a tDCS study in real traffic. At this time, we can conclude that tDCS is a useful tool in the examination of the causal roles of a targeted brain region in everyday life situations.

Competing interests

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