Temporal effects of tDCS on motor learning behavior

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Abstract. Transcranial direct current stimulation (tDCS) can improve motor learning. However, the effects of tDCS on the performance of a motor learning task, the choice reaction time task, remain elusive. Here, we examined the effects of tDCS on the learning and memory of a 4-choice visual-motor reaction time task (4-ChRT). Participants were randomly assigned to three tDCS groups: before (tDCSbefore), during (tDCSduring), or after ($tDCS_{after}$) motor practice, and two control groups, with (CON_{mp}) and without (CON) motor practice. We studied the reaction time and error rate of the 4-ChRT task before (Pre), during, and 24 h (Post) after the motor practice and tDCS. We found that motor practice can improve motor learning and tDCS during motor practice can most effectively reduce reaction time and error rate. These results will shed light on future study of using non-invasive brain stimulation to improve motor function in patients with motor disorders.

1. Introduction

There are two common explanations for better performance after practice: online skill gains, which is enhanced ability immediately after practice, and offline skill gains, long term improvements from memory consolidation. Learned skills result in structural and functional changes in the nervous system. Transcranial direct current stimulation (tDCS) is a non-invasive stimulation technique that has the capacity to enhance functions of the brain through modulating cortical excitability [1]. tDCS is thought to affect motor learning and retention when placed at the primary motor cortex (M1), on the opposite side of the dominant hand.

Changes in the motor learning can be manifested in the reaction time. Studies suggest that the best types of reaction time tasks are thought to be four-choice tasks, where participants are asked to react to a certain stimulus with pressing the corresponding key/button [2, 3]. This is because too many choices will result in more time spent reading the different options instead of measuring the reaction time taken by the participant, while only two or three choices would result in too large of a probability of getting a random answer correct and inaccurately measure reaction time [2]. This study uses reaction time and accuracy of these trials to explore the exact effect tDCS had on the reaction time task. Because of the possibility of fatigue interfering with test results, the post-test trial was done 24 hours after participants took part in motor practice, giving them a controlled length of time to rest. Another factor that would affect the results of applying tDCS was the ceiling effect [4].

There also seems to be different results depending on when tDCS was, as most studies only give tDCS during practice [5-8]. These practices also only show short-term improvement right after practice rather than the long-term possession of this skill [9, 10]. However, there are also studies that suggest tDCS applied before, during, or after had no effect on motor retention at all [11, 12]. In the present study, we will seek to examine how tDCS can change motor learning when applied at different time points of the practice.

2. Materials and methods

2.1. Participants

The data were retrieved from the online dataset Open Neuro (https://openneuro.org/). In total, there were 100 participants, with 68 being males, who took part in this investigation. Participants all had these common characteristics: right-handedness, no history of psychological disorders, neurological diseases, drugs/alcoholism, or use of neuropsychiatric medication. They also were not allowed to consume caffeine or alcohol the day prior to the experiment day(s). These boundaries are crucial to keeping variables irrelevant to the investigation (or dependent/independent variable) constant so interference on data collected is minimal. For example, drinking caffeine could strengthen attention while drug use or consuming alcohol could interfere with brain signals.

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2.2. Procedures

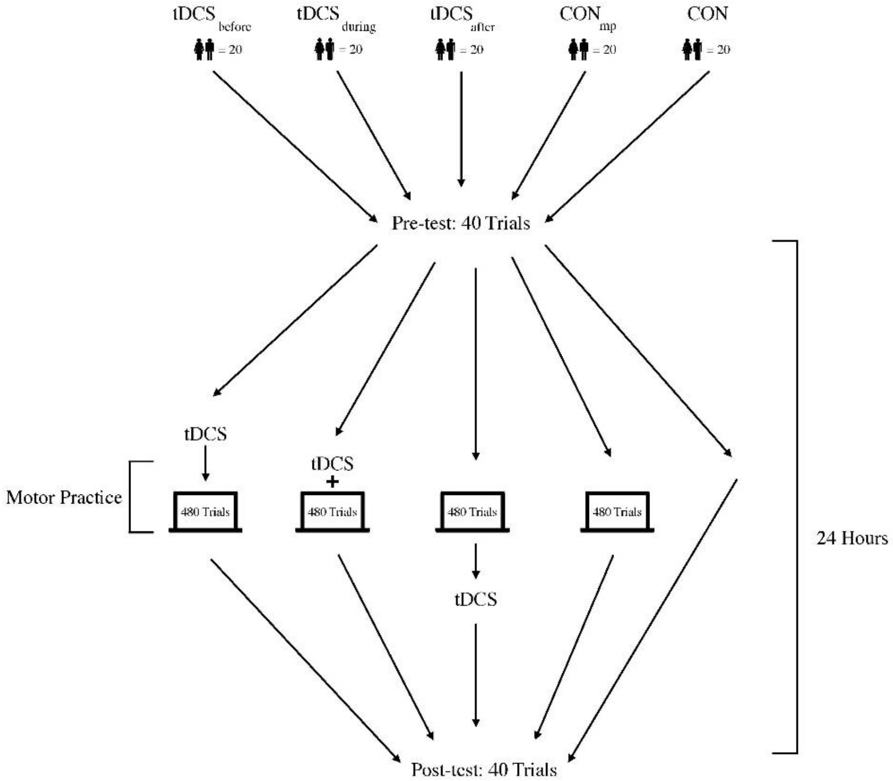

Figure 1. Experimental design. tDCS, transcranial direct current stimulation; CON, control group

Without motor practice; con_{mp}, control group with motor practice; $tdcs_{before}$ applied in three phases.

These participants were then separated randomly into groups of 20 (five groups in total) in order to manipulate the independent variable - the time of use of tDCS. Three of the five groups were given tDCS: one group received anodal transcranial direct current stimulation before motor practice ($tDCS_{before}$), one got tDCS during practice ($tDCS_{during}$), and the last received tDCS after motor practice ($tDCS_{after}$). The remaining two groups were established as control groups, one with motor practice (CON_{mp}) and one without (CON), which could also serve as a point of comparison against the use of tDCS at any point during the experiment. Participants were asked to complete 40 trials before and after motor practice (pre-test and post-test). Then the motor practice was made up of 12 of these 40-trial blocks (Figure 1), which was determined through studies suggesting fatigue could increase reaction time after around 480 trials [8].

2.3. tDCS

For the tDCS, a saline-soaked sponge that had been connected to a direct-current (DC) stimulator was used to induce 1-mA currents. This anode electrode was placed and stimulated at left M1, since it plays an important role in motor retention, while the cathode electrode was positioned at the right supraorbital cortex [13].

2.4. Reaction-time task

The task that participants were to complete was a reaction time task called four-choice reaction-time task (4-ChRT). In this task, participants were first told which keys correspond to which visual stimulus. Then, they were to press different keys (C, V, B, N) with their right, or dominant, hand in reaction to a visual for 500 ms while the rest of the squares remained blank, and the task was to press the correct key that matched it as fast as possible. The visuals shown were all in the same format with the only differences being the values/categories of the independent variable.

2.5. Data processing and analysis

The computer then collected the reaction time and the number of errors (if participants pressed the right key or not) in each block of experimentation (40 trials). Then this data was processed and calculated into mean, standard deviation, and variance. Graphs were created for each experimental group to show differences in reaction time (RT) over time (block number).

3. Results

First, we tested the reaction time before motor practice or tDCS and found no significant difference between groups (one-way analysis of variance (ANOVA): CON = 433.6 ± 12.09 ms, CON_{mp} = 435.3 ± 10.95 ms, $tDCS_{before}$ = 432.0 ± 9.167 ms, $tDCS_{during}$ = 429.7 ± 8.549 ms, $tDCS_{after}$= 429 ± 7.468 ms; n = 20, 20, 20, 20, 20; p = 0.2343, F test) (Figure 2). Interestingly, after motor practice and/or tDCS, the reaction times were significantly reduced in every group next day (Figure 3A, CON pre = 433.6 ± 12.09 ms, post = 399.3 ± 10.45 ms; n = 20, 20; $p < 0.0001$, paired t-test; Figure 3B, CON_{mp} pre = 435.3 ± 10.95 ms, post = 369.6 ± 9.883 ms; n = 20, 20; $p < 0.0001$, paired t-test; Figure 3C, $tDCS_{before}$ pre = 432.0 ± 9.167 ms, post = 352.3 ± 8.955 ms; n = 20, 20; $p < 0.0001$, paired t-test; Figure 3D, $tDCS_{during}$ pre = 429.7 ± 8.549 ms, post = 317.0 ± 8.378 ms; n = 20, 20; $p < 0.0001$, paired t-test; Figure 3E, $tDCS_{after}$pre = 429.8 ± 7.468 ms, post = 349.4 ± 9.733 ms; n = 20, 20; $p < 0.0001$, paired t-test). Moreover, there is a significant difference in the reaction time next day after motor practice and/or tDCS between groups (Figure 3F, one-way ANOVA: CON = 399.3 ± 10.45 ms, CON_{mp} = 369.6 ± 9.883 ms, $tDCS_{before}$ = 352.3 ± 8.955 ms, $tDCS_{during}$ = 317.0 ± 8.378 ms, $tDCS_{after}$= 317.0 ± 8.378 ms; n = 20, 20, 20, 20, 20; $p < 0.0001$, F test. CON vs. CON_{mp} : $p < 0.0001$, post hoc multiple comparison test; CON vs. $tDCS_{before}$: p <0.0001, post hoc multiple comparison test; CON vs. $tDCS_{during}$: $p < 0.0001$, post hoc multiple comparison test; CON vs. $tDCS_{after}$: $p < 0.0001$, post hoc multiple comparison test; CON_{mp} vs.. $tDCS_{before}$: $p < 0.0001$, post hoc multiple comparison test; CON_{mp} vs. tDCSdruing: $p < 0.0001$, post hoc multiple comparison test; CON_{mp} vs. $tDCS_{after}$: $p < 0.0001$, post hoc multiple comparison test; $tDCS_{before}$ vs. $tDCS_{during}$: $p < 0.0001$, post hoc multiple comparison test; $tDCS_{during}$ vs. $tDCS_{after}$: $p < 0.0001$, post hoc multiple comparison test). These data suggest that motor practice and tDSC can improve motor learning and reduce reaction time, and it is the most effective to apply tDCS during motor practice.

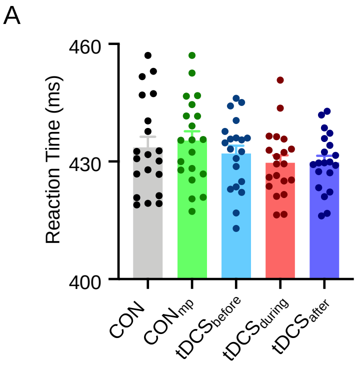

Figure 2. Reaction times before motor practice and tDCS.

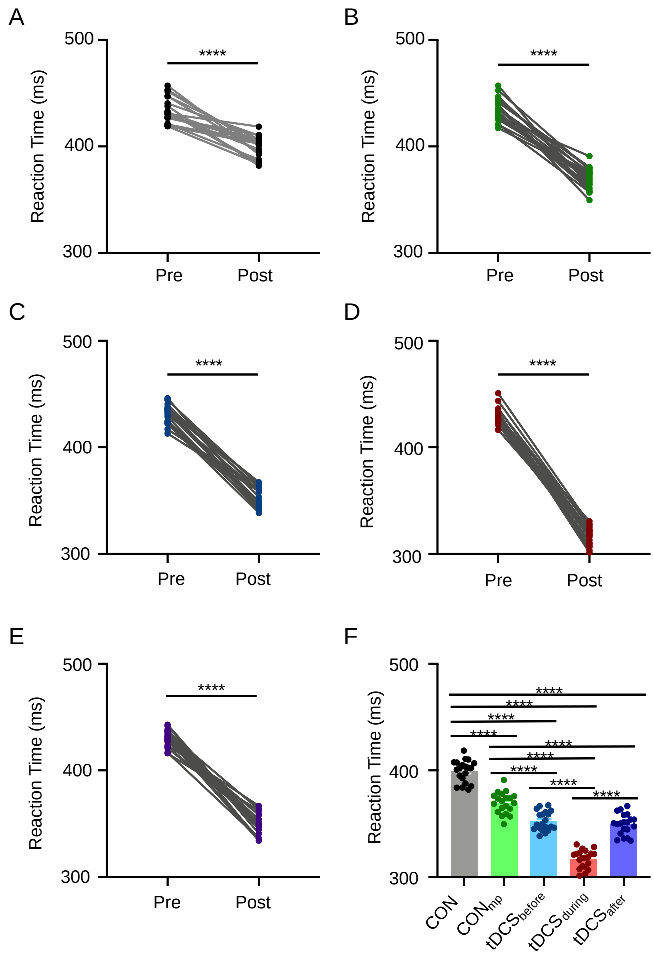

Figure 3. Effects tDCS on reaction time the next day after motor practice. ****P < 0.0001; error bar = SEM.

Next, we compared the reaction times before and right after motor practice and/or tDCS. We found that reaction times were significantly reduced right after motor practice or motor practice combined with tDCS at different time points (Figure 4A, CON_{mp} pre = 435.3 ± 10.95 ms, post = 402.4 ± 10.72 ms; n = 20, 20; $p < 0.0001$, paired t-test; Figure 4B, $tDCS_{before}$ pre = 432 ± 9.167 ms, post = 381.4 ± 8.099 ms; n = 20, 20; $p < 0.0001$, paired t-test; Figure 4C, $tDCS_{during}$ pre = 429.7 ± 8.549 ms, post = 349.5 ± 10.20 ms; n = 20, 20; $p < 0.0001$, paired t-test; Figure 4D, $tDCS_{after}$pre = 429.8 ± 7.468 ms, post = 375.3 ± 8.452 ms; n = 20, 20; $p < 0.0001$, paired t-test). We also found a significant difference in reaction times right after motor practice or motor practice combined with tDCS at different time points (Figure 4E, one-way ANOVA: CON_{mp} = 402.4 ± 10.72 ms, $tDCS_{before}$ = 381.4 ± 8.099 ms, $tDCS_{during}$ = 349.5 ± 10.20 ms, $tDCS_{after}$= 375.3 ± 8.452 ms; n = 20, 20, 20, 20; $p < 0.0001$, F test. CON_{mp} vs. $tDCS_{before}$: $p < 0.0001$, post hoc multiple comparison test; CON_{mp} vs. tDCSdruing: $p < 0.0001$, post hoc multiple comparison test; CON_{mp} vs. $tDCS_{after}$: $p < 0.0001$, post hoc multiple comparison test; tDCSbefore vs. $tDCS_{during}$: $p < 0.0001$, post hoc multiple comparison test; $tDCS_{during}$ vs. $tDCS_{after}$: $p < 0.0001$, post hoc multiple comparison test). These data suggest that applying tDCS during motor practice the most effectively reduced reaction time right after motor practice.

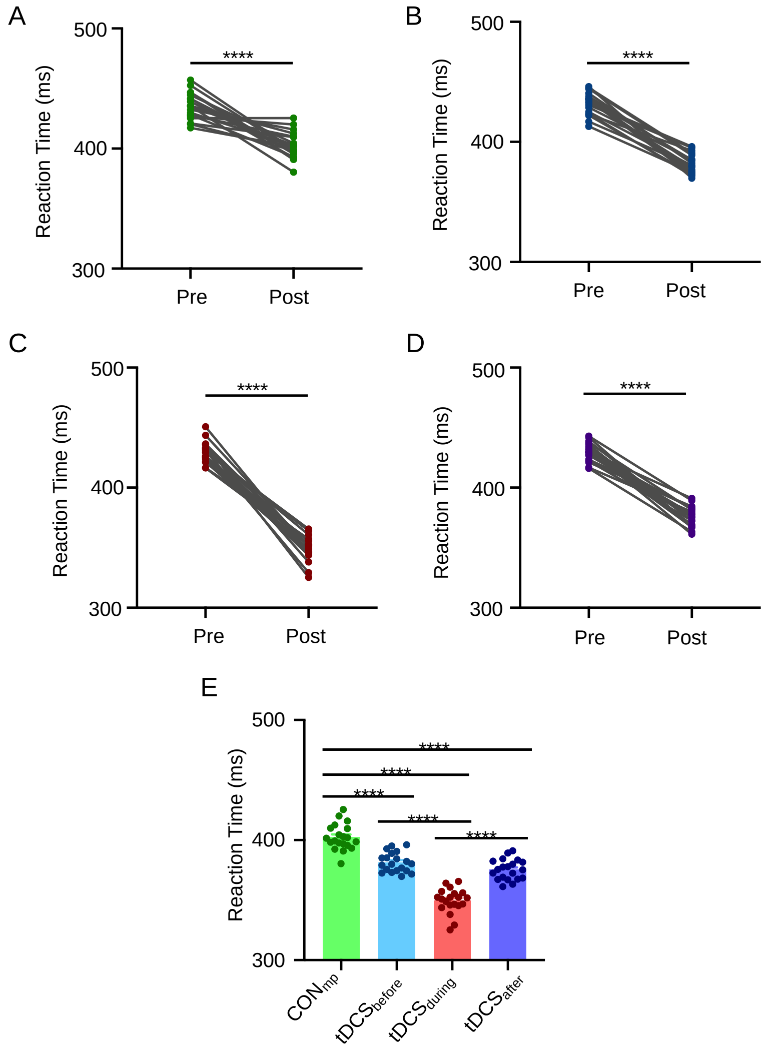

Figure 4. Effects of tDCS on reaction time right after motor practice. ****, P < 0.0001; error bar = SEM.

Finally, we examined error rate before and after motor practice with tDCS. We found no significant differences before motor practice and tDCS (Figure 5, one-way ANOVA: CON = 9.523 ± 1.100, CON_{mp} = 9.742 ± 1.095, $tDCS_{before}$ = 9.728 ± 1.124, $tDCS_{during}$ = 10.43 ± 1.087, $tDCS_{after}$= 10.30 ± 0.9029; n = 20, 20, 20, 20, 20; $p = 0.325$, F test). However, we observed a significant difference after motor practice and tDCS (Figure 6, one-way ANOVA: CON = 7.805 ± 0.8084, CON_{mp} = 5.834 ± 0.6190, $tDCS_{before}$ = 4.005 ± 0.3650, $tDCS_{during}$ = 2.068 ± 0.1806, $tDCS_{after}$= 3.917 ± 0.3160; n = 20, 20, 20, 20, 20; $p <0.0001$, F test). Furthermore, we found motor practice reduced error rate and tDCS during motor practice most effectively reduced error rate (CON vs. CON_{mp}: p = <0.0001, post hoc multiple comparison test; CON vs. $tDCS_{before}$: $p < 0.0001$, post hoc multiple comparison test; CON vs. $tDCS_{during}$: $p < 0.0001$, post hoc multiple comparison test; CON vs. $tDCS_{after}$: p = <0.0001, post hoc multiple comparison test; CON_{mp} vs. $tDCS_{before}$: $p < 0.0001$, post hoc multiple comparison test; CON_{mp} vs.

tDCSdruing: $p < 0.0001$, post hoc multiple comparison test; CON_{mp} vs. $tDCS_{after}$: $p < 0.0001$, post hoc multiple comparison test; $tDCS_{before}$vs. $tDCS_{during}$: $p < 0.0001$, post hoc multiple comparison test $tDCS_{during}$ vs. $tDCS_{after}$ $tDCS_{after}$: $p < 0.0001$, post hoc multiple comparison test). Together, these results indicate tDCS during motor practice is the optimal way to improve motor learning.

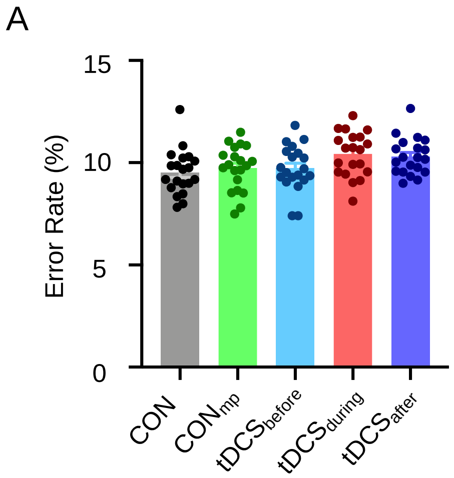

Figure 5. Error rate before motor practice.

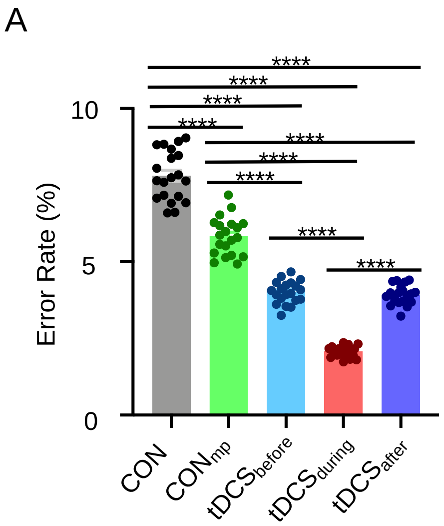

Figure 6. Error rate after motor practice and tDCS. ****, P < 0.0001; error bar= SEM.

4. Discussion

This study was conducted to investigate how tDCS applied at different times affects the learning of an explicit-learning paradigm. TDCS was applied before during and after motor practice to different experimental groups. The difference between anodal and cathodal is that one increases the rate of motor sequence learning while cathodal tDCS decreases the rate; but both anodal and cathodal tDCS applied before motor practice/task made for a slower rate of learning.

Hebbian synaptic plasticity mechanisms in interneurons like long-term potentiation (LTP)-like changes are what allows for motor learning in the primary motor cortex [14-16]. LTP-like plasticity also can destabilize already established cortical networks since they operate on positive feedback [17]. This results in unregulated cortical activity, which prevents new dynamic modifications to be added. Many different regulatory metaplastic mechanisms have been proposed in attempts to prevent this destabilization of cortical networks through keeping neural activity within a practical range [18, 19].

This timing-dependent interaction between anodal tDCS and motor learning could be explained by metaplastic mechanisms, which corresponds to a previous study, which showed slowed motor learning when anodal tDCS was applied prior motor learning. These diverse results on the effect of tDCS could also be because of the different tasks used [4].

There are two ways tDCS could affect learning: by decreasing the total amount of learning done or decrease the rate of learning. Both methods were influenced by tDCS in this study, since anodal tDCS was applied during motor learning and increased the rate of learning while cathodal stimulation applied resulted in a decrease in both the amount and rate of learning.

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