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The Effect of Cerebellar Transcranial Direct Current Stimulation on A Throwing Task Depends on Individual Level of Task Performance

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Abstract—The effect of cerebellar transcranial direct current stimulation (tDCS) on motor performance remains controversial. Some studies suggest that the effect of tDCS depends upon task-difficulty and individual level of task performance. Here, we investigated whether the effect of cerebellar tDCS on the motor performance depends upon the individual's level of performance. Twenty-four naïve participants practiced dart throwing while receiving a 2-mA cerebellar tDCS for 20 min under three stimulus conditions (anodal-, cathodal-, and sham-tDCS) on separate days with a double-blind, counter-balanced cross-over design. Task performance was assessed by measuring the distance between the center of the bull's eye and the dart's position. Although task performance tended to improve throughout the practice under all stimulus conditions, improvement within a given day was not significant as compared to the first no-stimulus block. In addition, improvement did not differ among stimulation conditions. However, the magnitude of improvement was associated with an individual's level of task performance only under cathodal tDCS condition ($p < 0.05$). This resulted in a significant performance improvement only for the sub-group of participants with lower performance levels as compared to that with sham-tDCS ($p < 0.05$). These findings suggest that the facilitation effect of cerebellar cathodal tDCS on motor skill learning of complex whole-body movements depends on the level of an individual's task performance. Thus, cerebellar tDCS would facilitate learning of a complex motor skill task only in a subset of individuals.

Key words: motor skill, motor learning, cerebellum, cathodal, dart.

INTRODUCTION

Many studies have involved an attempt to facilitate human motor learning by modulating cortical excitability with non-invasive brain stimulation (for reviews, see Reis and Fritsch, 2011; Buch et al., 2017). One of the most common types of stimulation is transcranial direct current stimulation (tDCS). Human neurophysiological studies have demonstrated that tDCS can modulate cortical excitability in the targeted region (Nitsche and Paulus, 2000; Nitsche et al., 2003; Galea et al., 2009), and behavioral studies have shown that tDCS to the cerebellum facilitates the learning of discrete motor tasks (Galea et al., 2011; Herzfeld et al., 2014; Cantarero et al., 2015; Jalali et al., 2017). However, it has been noted that the effect of tDCS varies across tasks and individuals (Li et al., 2015; Jalali et al., 2017).

The effect of tDCS on the parietal cortex depends upon task-difficulty as well as on an individual's capability for performance of the cognitive task (Jones and Berryhill, 2012; Weiss and Lavidor, 2012). Similarly, the effect of cerebellar tDCS might also be dependent upon task-difficulty and/or an individual's capability for performing a given motor task. This assumption is supported by the finding that anodal tDCS to the cerebellum facilitates visuomotor adaptation (Galea et al., 2011; Jalali et al., 2017), force-field adaptation performed with the arm (Herzfeld et al., 2014), and learning of a skill task involving sequential force production using the thumb and index finger (Cantarero et al., 2015). However, similar anodal cerebellar tDCS does not modulate performance of a dynamic balance task involving a complex whole-body movement (Steiner et al., 2016). Therefore, the effect of cerebellar tDCS on the performance of complex whole-body movements appears to be different from that of simple movements. One factor which has to be considered with complex movements involves individual differences in performance. While a particular complex motor task might prove difficult for some participants, the same

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Abbreviation: tDCS, transcranial direct current stimulation.

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motor task could be relatively easy for other participants. Consequently, the effect of cerebellar tDCS on motor learning would likely differ for the above two groups.

In the present study, we utilized dart throwing to investigate whether the effect of cerebellar tDCS on motor learning was associated with an individual's level of motor performance. Dart throwing is a moderately difficult, complex whole-body movement which involves both multi-joint coordination and postural control. The level of difficulty for this task might differ substantially between individuals. We hypothesized that the effect of cerebellar tDCS on dart performance, if any, would be associated with the individual's level of dart performance, which in turn would reflect the level of task difficulty for the individual.

EXPERIMENTAL PROCEDURES

Participants

Twenty-four healthy male novices participated in the study (23 ± 3 years of age; mean ± one standard deviation (S.D.), range 19–31 years). Handedness was evaluated with the Edinburgh Inventory (Oldfield, 1971). All participants received a detailed explanation of the experimental procedures before the study, and written informed consent was obtained from all participants. The study was approved by the Human Research Ethics committee of Waseda University and the experiment was carried out according to the principles and guidelines of the Declaration of Helsinki (1975).

Motor task; dart throwing

The participants performed dart throwing using their right hand. Although one participant was deemed a left handed by the Edinburgh Inventory (Oldfield, 1971), we asked that participant to throw with the right hand since his answer to the questionnaire as to "throwing a ball" was right hand. A dartboard's bull's-eye was set at 1.73 m above the floor, and 2.44 m away from the place where participants were asked to stand. For the task, we asked the participants to aim at the center of the bull's-eye. We did not give any specific instructions about stance, gripping or throwing. We did ask them to throw with the same motion throughout the entire experiment.

tDCS stimulation

A 2-mA tDCS (DC-stimulator-Pulse M, neuroConn, Germany) was delivered via two saline-soaked surface sponge electrodes ($5 \times 5\ \text{cm} = 25\ \text{cm}^2$). Since the participants threw the darts using their right hand, we stimulated the right cerebellum. The target electrode was placed over the right cerebellum, 3 cm lateral to the inion, and the reference electrode was placed over the right buccinator muscle (Cantarero et al., 2015). We utilized three types of stimulation: anodal, cathodal and sham. For anodal and cathodal stimulation, tDCS was applied for 20 min. For sham stimulation, tDCS was applied for 30 s with the same polarity as the anodal stimulation. A fade-in and fade-out period was set at 30 s at the beginning and end of stimulation.

Procedure

Each participant completed three experimental sessions under each stimulation condition (anodal, cathodal or sham). A session was comprised of consecutive two days; the first "learning" day and the second "retention" day. The sessions were conducted at least 7 days apart in order to minimize the risk of contamination via carry-over effects from previous tDCS application. The order of stimulation types was counterbalanced across participants. Each participant started all experimental sessions at the same time on each day to minimize the influence of circadian rhythm on the level of motor performance and/or on the effect of neuromodulation (Drust et al., 2005; Sale et al., 2007).

Each session consisted of 6 task blocks with an inter-block interval of 1 min for day 1 (block 1 to 6), and only 1 task block for day 2 (block 7) (Fig. 1). Each block consisted of 25 trials (i.e. dart throws). The inter-throw interval was set at 10 s. Prior to starting the first block on each day, the participants threw darts three times as familiarization trials. In the 1st block, the participants performed the task without receiving any stimulation. From the 2nd block to the end of the 5th block (i.e. 20 min), tDCS was applied in the anodal and cathodal conditions. The participants performed the 6th block without receiving any stimulation. On day 2, the participants performed a 7th block without tDCS. The starting time for a 7th block in day 2 was adjusted so that the block started at the same time as that for the 1st block on day 1.

Data analysis

Using a video camera (GC-PX1, JVC, JAPAN), we made a continuous recording of the dartboard throughout the experiment. As an index of task performance, we digitized the distance between the center of the bull's eye and the dart's stick point using motion analysis software (Frame Dias IV, DKH, Japan). This analysis was performed by an investigator blinded to the tDCS assignment. We then averaged the distance for each block (i.e. 25 trials). To evaluate improvement of the dart performance across task blocks, we calculated the difference between the average distance for the 1st block and that of each following block. We averaged the magnitude of improvements from block 2 to block 6. To compare the effect of stimulation on the degree of improvement, paired t-tests with the Bonferroni correction were applied. We also analyzed whether the improvement was significant as compared to the block 1 for each condition.

We also evaluated the individual level of dart performance for each participant by computing the average of the first block for the 1st session (= 25 throws). To reduce the influence of day-to-day fluctuation, we also evaluated the average of the first blocks for three conditions (= 75 throws). This average was used in an additional analysis. We confirmed that the average distance for the first block did not differ among the three stimulus conditions ($p > 0.5$, $d < 0.1$). Then, to investigate the relationship between the