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SHORT REPORTS

Cerebellar Transcranial Direct Current Stimulation Enhances Motor Learning in a Complex Overhand Throwing Task

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Abstract

Cerebellar transcranial direct current stimulation (c-tDCS) enhances motor adaptation, skill acquisition, and learning in relatively simple motor tasks. The purpose was to examine the influence of c-tDCS on motor learning in a complex overhand throwing task. Forty-two young adults were randomized to a c-tDCS group or a SHAM group and completed a practice session and a retention session. The practice session involved an overhand throwing task to a small target (6 m away) in a pre-test block, 6 practice blocks, a post-test block, and a retention-test block (24 h later). c-tDCS or SHAM was applied during overhand throwing in the practice blocks. The decline in endpoint error was greater for the tDCS group compared to SHAM at the end of practice ($P = 0.019$) and at retention ($P = 0.003$). The findings indicate that a single application of c-tDCS enhances motor learning in a complex overhand throwing task.

Keywords Transcranial direct current stimulation · Motor learning · Overhand throwing · Motor adaptation

Introduction

A single application of transcranial direct current stimulation (tDCS) delivered to motor cortex (M1) during practice usually enhances motor skill [1]. Although M1 has been the most common brain area targeted with tDCS, several studies have demonstrated that cerebellar tDCS (c-tDCS) can improve motor adaptation [2], skill acquisition, and learning [3]. Furthermore, M1-tDCS and c-tDCS could lead to different behavioral outcomes due to the distinct functions of the cerebellum and M1 in motor learning [4]. Accordingly, c-tDCS could have comparable or even greater effects on motor performance than M1-tDCS in certain experimental paradigms or specific motor tasks [4].

Several c-tDCS motor skill studies have shown accelerated learning with motor adaptation tasks and relatively simple unilateral tasks with the hand and arm [5]. However, it is unknown if c-tDCS can improve motor learning in a complex, multi-joint task involving whole-body coordination with substantial endpoint accuracy requirements, which could be more applicable to occupational tasks, sports, and daily living activities [6]. Therefore, the purpose was to examine the influence of c-tDCS on motor learning in an overhand throwing task. Based on a previous c-tDCS study involving a pinch grip task [3], we hypothesized that c-tDCS applied during practice would enhance motor learning. A 3D overhand throwing task was chosen due to the complexities of the task that each involve cerebellar activity: (1) timing and finger force opening in throwing [7]; (2) unconstrained, multi-joint movement control such as the prediction and utilization of joint interaction torques along with agonist/antagonist muscle interactions [8]; and (3) error detection in goal-directed movements [9].

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Materials and Methods

Participants

Forty-two right-handed males ($n = 21$ per group; age 25 ± 3.9) who were not currently participating in a throwing sport provided written informed consent. All procedures were approved by the University's IRB and conducted according to the Declaration of Helsinki.

Procedures

The study was a randomized, between-subjects, SHAM-controlled, double-blind experimental design. Subjects completed two experimental sessions involving 3D unconstrained, overhand throwing on consecutive days at the same time each day. The protocol (Fig. 1a) comprised a pre-test block, 6 practice blocks while receiving c-tDCS or SHAM, a post-test block, and (24 h later) a retention-test block.

tDCS

A NeuroConn Stimulator was placed in a small, tight-fitting backpack that did not restrict performance. Anodal c-tDCS was delivered using previously determined effective parameters (duration 25 min; current 2 mA; anode 3 cm right of the inion; cathode right buccinator muscle) to the cerebellum ipsilateral to the right hand through rubber electrodes (5 × 5 cm) enclosed in saline-soaked sponges held in place with rubber straps. For SHAM, the current was ramped up and down over 30 s.

Overhand Throwing Task

The overhand throwing task was executed identically in all trial blocks, except that the stimulator was not turned on in the test blocks. Subjects stood behind a line 6 m from a wall, which had a large target area with a very small (1 cm diameter) "bull's-eye" center (Fig. 1b). Participants threw a tennis ball with the right arm (similar to a baseball throw) and were instructed to perform each throw as accurately as possible by trying to hit the target center. Subjects used visual feedback of the ball's endpoint relative to the target center after each trial to facilitate the goal of minimizing error distance on subsequent trials. The ball was covered with red chalk between blocks, so that marks were made denoting final position upon hitting the target area. Each mark was recorded with a small trial-numbered sticker after each trial. After each trial block, the sticker endpoint coordinates were measured and recorded by

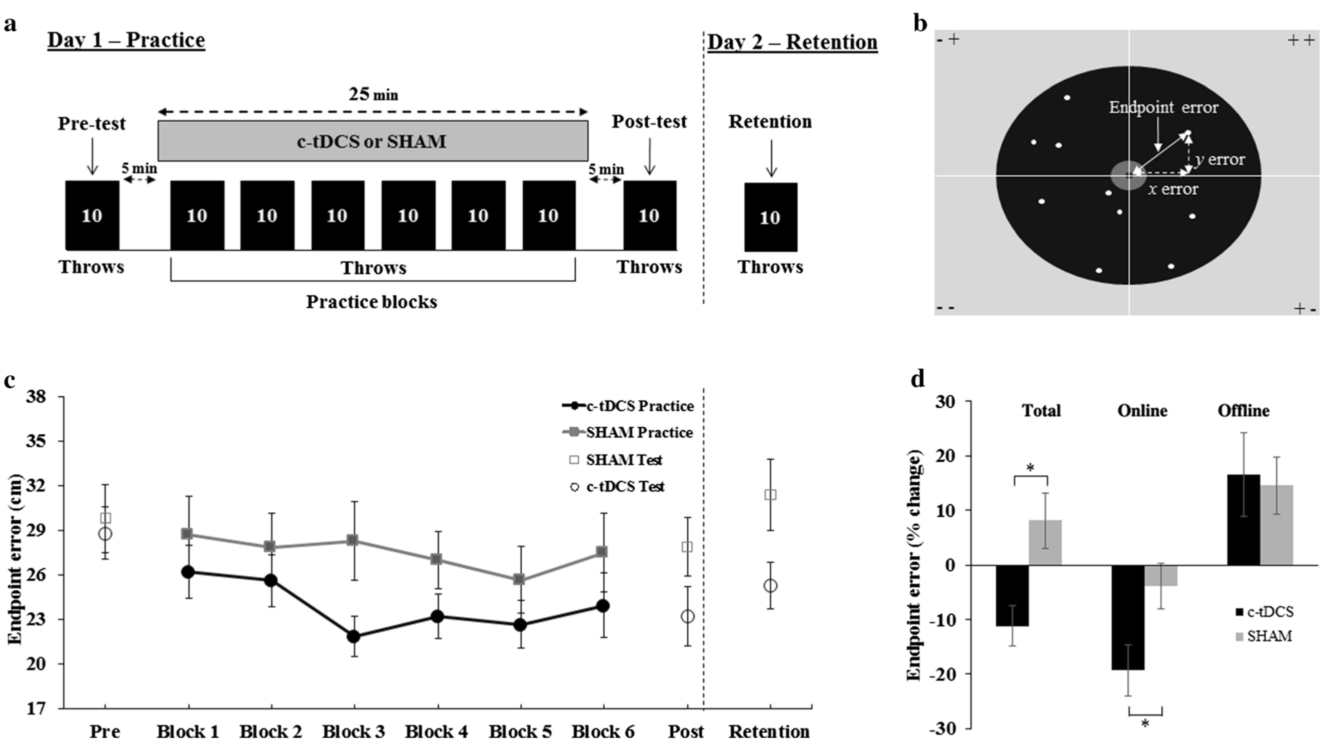

Fig. 1 Experimental protocol and results. **a** Schematic of the experimental protocol that comprised c-tDCS electrode placement, a pre-test block, 6 practice blocks (performed concurrent with c-tDCS or SHAM), and a post-test block on day 1 (practice session), followed by a retention-test block (24 h later) on day 2 (retention session). Five-minute intervals were implemented before and after the 25 min of c-tDCS and the pre-test and post-test blocks, respectively. Note that the stimulator was turned on for 3 min while subjects stood quietly before performing the first practice block and a rest interval of 2 min was given between practice blocks. **b** Target area and assessment of endpoint error. The entire target area was 1.27 m in length by 1 m in width, and the target circle was 1.71 m from the floor. **c** Endpoint error for the c-tDCS (circles) and SHAM (squares) groups for the test (open symbols) and practice blocks (closed symbols). The endpoint error was nearly identical for the two groups in the pre-test. However, the tDCS group exhibited greater declines in endpoint error in the post-test and especially the retention-test block ($P = 0.04$) compared to the SHAM group. **d** Total learning ($P = 0.003$) and online learning ($P = 0.019$) were significantly greater for the tDCS group compared to the SHAM group, whereas offline learning was similar for the two groups ($P = 0.883$)

investigators. Finally, the stickers were removed from the target area between blocks and the process repeated.

Data Analysis and Statistics

Endpoint error was the dependent variable and quantified as the shortest distance between the target center's x, y coordinates and the ball's endpoint for each trial using the Pythagorean theorem [10, 11]. Similar to a previous multi-day c-tDCS study [3] and M1-tDCS studies [12–14], the data were analyzed in two ways. First, ANOVA was used to determine that differences existed in total learning. Second, the relative contributions of online (within-day) and offline learning (between-day) to total learning were analyzed.

Separate ANOVAs were conducted on the test blocks and the practice blocks as c-tDCS was applied only during the practice blocks. Accordingly, a two-way ANOVA [2 *group* (c-tDCS, SHAM) × 3 *test* (pre, post, and retention)] with repeated measures on *test* was used to compare endpoint error in the test blocks, whereas a two-way ANOVA [2 *group* (c-tDCS, SHAM) × 6 *block* (1–6)] with repeated measures on *block* was used to compare endpoint error for the practice blocks. Fisher LSD post hoc tests were used to locate differences among pairs of means.

Total learning was calculated as the percent change in endpoint error between the pre-test block and the retention-test block, whereas online learning was the percent change between the pre-test block and the post-test block and offline learning was the percent change between the post-test block and the retention-test block. In all cases, percent change in endpoint error between groups was compared with two-tailed unpaired t tests. Data are indicated as means ± standard errors in Fig. 1 and means ± standard deviations in Table 1.

Results

For the test blocks, there was a significant *group* × *test* interaction (F[2, 80] = 3.427, P = 0.037; Fig. 1c). Post hoc analysis of the interaction indicated that endpoint error was lower in the retention-test block for the c-tDCS compared to the SHAM group (P = 0.04). However, the post-test block differences were not significant (P = 0.104). Finally, endpoint error was similar between groups for the pre-test (P = 0.748). There was also a significant main effect for *test* (F[2, 80] = 7.433, P = 0.001), and post hoc analysis indicated that endpoint error was significantly lower in the post-test compared to the pre-test (P = 0.001) and the retention-test (P = 0.013). The main effect for group was not significant (F[1, 40] = 2.241, P = 0.142). For the practice blocks, Mauchly's test of sphericity was significant (P = 0.012); therefore, a Huynh-Feldt correction was used. There was a significant main effect for *block* (F[4.4, 176.8] = 2.355, P = 0.049; Fig. 1c), and post hoc analyses indicated that endpoint error was lower for practice blocks 3–5 (P = 0.026, P = 0.028, P = 0.014, respectively) compared to practice block 1. The main effect for *group* (F[1, 40] = 1.951, P = 0.17) and *group* × *test* interaction (F[4.4, 176.8] = 0.904, P = 0.471) was not significant.

Both total learning and online learning were significantly greater for the tDCS compared to the SHAM group (P = 0.003 and P = 0.019, respectively). However, offline learning was similar between groups (P = 0.833; Fig. 1d).

Discussion

The main finding was that a single c-tDCS session improved motor skill acquisition and learning in a complex overhand throwing task to a greater extent than practice alone. Specifically, c-tDCS elicited greater online effects as decreases in endpoint error were much larger over the course of practice and in the post-test block in the c-tDCS group, despite nearly identical pre-test endpoint error values for the two groups. Interestingly, about half of these improvements were evident in the first practice block after c-tDCS had been applied for only 3 min before and during this initial block. These effects are similar to previous multi-day c-tDCS [3] and M1-tDCS studies [12–14] where most of the skill acquisition advantages that were seen on day 1 occurred primarily in the first few practice blocks and were maintained or slightly increased with further practice by the end of day 1. There was also greater total motor learning since endpoint error was lower in the retention-test block (day 2) for the c-tDCS group. However, this was mainly a consequence of the lower endpoint error levels attained by the c-tDCS group at the end of day 1 (online effects), because endpoint error increases between the post-test and retention-test were comparable between groups.

These findings are generally consistent with prior acute c-tDCS studies that involved adaptive motor learning in walking

Table 1 Mean (SD) of the endpoint error (cm) for each block of overhand throwing trials for the c-tDCS and SHAM groups

	Pre	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6	Post	Retention
c-tDCS	28.83 (8.13)	26.19 (8.23)	25.62 (8.02)	21.86 (6.20)	23.19 (6.89)	22.67 (7.49)	23.94 (9.96)	23.20 (9.16)	25.30 (7.26)
SHAM	29.76 (10.47)	28.72 (11.67)	27.85 (10.54)	28.25 (12.05)	26.99 (8.88)	25.65 (10.33)	27.50 (12.00)	27.86 (8.96)	31.39 (10.95)

[15] and two-dimensional arm movement tasks [2, 4]. The current results also confirm and extend previous findings that c-tDCS applied over 3 days substantially increased force accuracy during a visuo-motor isometric pinch grip task [3]. This is important because many motor learning principles derived from simple tasks do not always extend to complex tasks and studies utilizing complex tasks are essential to understanding motor control and learning [6]. Future studies should examine the effects of multi-day c-tDCS on motor learning in complex motor tasks in populations such as highly skilled performers, older adults, and in movement disorders.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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