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1 Short Communication

2 Cathodal transcranial direct current stimulation over left
3 dorsolateral prefrontal cortex area promotes implicit motor
4 learning in a golf putting task

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1 **Abstract**

2 *Background:* Implicit motor learning is characterized by low dependence on working memory and stable
3 performance despite stress, fatigue, or multi-tasking. However, current paradigms for implicit motor
4 learning are based on behavioral interventions that are often task-specific and limited when applied in
5 practice.

6 *Objective:* To investigate whether cathodal transcranial direct current stimulation (tDCS) over the left
7 dorsolateral prefrontal cortex (DLPFC) area during motor learning suppressed working memory activity
8 and reduced explicit verbal-analytical involvement in movement control, thereby promoting implicit
9 motor learning.

10 *Methods:* Twenty-seven healthy individuals practiced a golf putting task during a Training Phase while
11 receiving either real cathodal tDCS stimulation over the left DLPFC area or sham stimulation. Their
12 performance was assessed during a Test phase on another day. Verbal working memory capacity was
13 assessed before and after the Training Phase, and before the Test Phase.

14 *Results:* Compared to sham stimulation, real stimulation suppressed verbal working memory activity after
15 the Training Phase, but enhanced golf putting performance during the Training Phase and the Test Phase,
16 especially when participants were required to multi-task.

17 *Conclusion:* Cathodal tDCS over the left DLPFC may foster implicit motor learning and performance in
18 complex real-life motor tasks that occur during sports, surgery or motor rehabilitation.

19

20 **Keywords**

21 Cathodal tDCS; Left dorsolateral prefrontal cortex; Verbal working memory; Implicit motor learning;

22

1 **Introduction**

2 Contemporary theories of motor learning argue that motor skills can be acquired explicitly or implicitly
3 [1,2]. Explicit motor learning is intentional and uses working memory to manage verbal-analytical aspects
4 of learning, such as the utilization of verbal instructions, monitoring and control of performance,
5 formation and testing of hypotheses, correction of errors, and the accumulation, retrieval and
6 implementation of declarative knowledge [3,4]. In contrast, implicit motor learning reduces verbal-
7 analytical involvement in motor control by encouraging limited dependence on working memory. This
8 form of learning has been shown to result in less conscious knowledge of the movements involved [5,6]
9 and performance with higher neural efficiency [7,8] than explicit motor learning, leaving the performer
10 more able to deal with stress [9-12] or fatigue [13,14], and to multi-task [15,16]. Although no form of
11 motor learning is purely implicit or explicit, researchers have deliberately attempted to devise implicit
12 motor learning paradigms that reduce conscious control of movements during learning and performance
13 of motor tasks. Such paradigms include dual-task learning [3,4,9,17,18], analogy learning [5,10,20], and
14 errorless learning [6,13,14,20]. However, all of these paradigms suppress working memory activity
15 indirectly by using task-specific behavioral interventions and may encounter limitations when applied in
16 practice [2].

17 Transcranial direct current stimulation (tDCS) is a noninvasive brain stimulation technique that
18 modulates cortical excitability in a polarity-dependent manner: anodal stimulation increases excitability,
19 whereas cathodal decreases it [21,22]. More specifically, tDCS over the left dorsolateral prefrontal cortex
20 (DLPFC) area has been shown to modulate working memory [23-25]. Hence, we hypothesized that
21 cathodal tDCS over the left DLPFC area during motor learning would suppress the use of working
22 memory and reduce explicit verbal-analytical involvement in movement control, thereby promoting
23 implicit motor learning.

24 **Material and methods**

1 *Participants*

2 Twenty-seven college students, right-handed with no golf experience, participated in the study to learn a
3 golf putting motor task while receiving either Real cathodal tDCS over the left DLPFC area (n = 14, mean
4 age = 21.5, SD = 2.28) or Sham stimulation (n = 13, mean age = 20.46, SD = 2.03). All research methods
5 were approved by the University's Institutional Review Board. Participants were asked to provide written
6 informed consent and were paid an honorarium of HK\$150 (approximately US\$20).

7 *Golf putting task*

8 The golf putting task required participants to putt standard white golf balls to a target hole (12cm in
9 diameter) on an artificial grass putting surface that was even and level. Putts were made from a distance
10 of 1.9m using a standard golf putter.

11 *Verbal working memory measure*

12 Verbal working memory capacity was measured using a counting recall task from the Automated
13 Working Memory Assessment (AWMA) [26]; participants were presented with a series of shapes and
14 were required to count aloud the number of red circles in each set of shapes. Afterwards, they had to
15 recall the number of red circles in each set of shapes in the correct sequence. Scores on the counting recall
16 task were derived by the AWMA program.

17 *Procedure*

18 The experiment was divided into a Training Phase and a Test Phase on two separate days. Participants
19 were instructed to putt as accurately as possible. In order to familiarize participants with the task, ten
20 warm-up trials were completed. The Training Phase consisted of 7 practice blocks, with 10 trials in each
21 block. The Test Phase employed an A-B-A reversal design consisting of three blocks of 10 trials. The first
22 and last blocks (Retention Test 1 and 2) were designed to assess the levels of performance of the two
23 groups after training. The second block of putts, the Multi-task Test, was performed in conjunction with a

1 secondary tone-counting task [4], which required participants to monitor and count the number of both
2 high and low pitch tones randomly generated by a computer every 2 seconds. Verbal working memory
3 capacity was tested using the counting recall task on three occasions: before the Training Phase, after the
4 Training Phase, and before the Test Phase.

5 *tDCS*

6 tDCS was delivered by a DC-Stimulator (NeuroConn, Ilmenau, Germany) and a pair of 50 x 50 mm
7 saline-soaked sponge electrodes. The stimulator was fitted onto a backpack so that it could comfortably
8 be carried by participants and did not interfere with their movements. The cathodal contact was placed
9 over the left DLPFC area (F3) and the anodal contact was placed over the right supraorbital area (FP2) in
10 accordance with the 10-20 international system for EEG electrode placement. For the Real Stimulation
11 (RS) learning group, a constant current of 1.5mA with 30-second fade in/out was applied throughout the
12 Training Phase, which took around 15-20 minutes. For the Sham Stimulation (SS) learning group, the
13 stimulator was turned off automatically after 15 seconds of 1.5 mA stimulation with 30-second fade
14 in/out.

15 **Results**

16 AWMA counting recall task scores were analyzed using a Group x Occasion (2 x3) repeated measures
17 ANOVA. The analysis revealed a significant main effect of Occasion ($P < 0.001$) and a Group x Occasion
18 interaction ($P = 0.038$). As shown in Table 1, the RS learning group did not display any significant
19 change in AWMA counting recall task scores after the Training Phase compared to before the Training
20 Phase ($P = 0.666$), whereas the SS learning group displayed higher scores ($P = 0.001$). However, the RS
21 learning group displayed higher AWMA counting recall task scores before the Test Phase compared to
22 after the Training Phase ($P = 0.018$), whereas the SS learning group displayed no change ($P = 0.915$).

23 **Table 1 about here**

1 left DLPFC during the Training Phase was only temporary, with no long-term adverse effect on
2 participants' verbal working memory capacity.

3 With respect to motor performance (i.e., putting score) the RS learning group performed better
4 than the SS learning group during both the Training and Test phases. In particular, the RS learning group
5 displayed better putting performance than the SS learning group during the Multi-task test (concurrent
6 tone-counting), suggesting that cathodal tDCS over the left DLPFC promoted performance that was more
7 implicit and automatic than the SS learning group. Stable motor performance when multi-tasking is a
8 standard outcome of implicit motor learning [1,2,4,6,13,14] and the findings are consistent with recent
9 claims that inhibition of the prefrontal cortex using cathodal tDCS encourages a shift in dominance from
10 the declarative (explicit) memory system to the non-declarative procedural (implicit) system [29].
11 Consequently, cathodal tDCS over the left DLPFC area may be a new tool with which to promote implicit
12 motor learning and performance of important real-life motor tasks in domains such as sport, surgery or
13 motor rehabilitation.

14

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17 of Hong Kong (Ref. No. 00005832).

18

1 **Legends**

2 Table 1. AWMA counting recall task scores of Real Stimulation (RS) and Sham Stimulation (SS)

3 learning groups before the Training Phase, after the Training Phase, and before the Test Phase.

4 Figure 1. Number of successful putts of Real Stimulation (RS) and Sham Stimulation (SS) learning

5 groups across the Training Phase (B1-7) and the Test Phase (Retention Test 1: R1, Multi-task Test: M,

6 Retention Test 2: R2).

7

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