Human Movement Science 66 (2019) 241–248

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

An acute application of transcranial random noise stimulation does not enhance motor skill acquisition or retention in a golf putting task

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ARTICLE INFO

Keywords:
Transcranial direct current stimulation
Transcranial magnetic stimulation
Motor skill
Motor learning
Golf

ABSTRACT

Transcranial random noise stimulation (tRNS) is a brain stimulation technique that has been shown to increase motor performance in simple motor tasks. The purpose was to determine the influence of tRNS on motor skill acquisition and retention in a complex golf putting task. Thirty-four young adults were randomly assigned to a tRNS group or a SHAM stimulation group. Each subject completed a practice session followed by a retention session. In the practice session, subjects performed golf putting trials in a baseline test block, four practice blocks, and a post test block. Twenty-four hours later subjects completed the retention test block. The golf putting task involved performing putts to a small target located 3 m away. tRNS or SHAM was applied during the practice blocks concurrently with the golf putting task. tRNS was applied over the first dorsal interosseus muscle representation area of the motor cortex for 20 min at a current strength of 2 mA. Endpoint error and endpoint variance were reduced across the both the practice blocks and the test blocks, but these reductions were not different between groups. These findings suggest that an acute application of tRNS failed to enhance skill acquisition or retention in a golf putting task.

1. Introduction

The use of non-invasive electrical brain stimulation techniques such as transcranial direct current stimulation (tDCS), transcranial alternating current stimulation (tACS), and transcranial random noise stimulation (tRNS) (Prichard, Weiller, Fritsch, & Reis, 2014; Saiote, Polania, Rosenberger, Paulus, & Antal, 2013; Terney, Chaieb, Moliadze, Antal, & Paulus, 2008) as interventions to improve motor performance has been increasing rapidly over the past several years due to promising findings in the majority of initial studies (Buch et al., 2017). tDCS has been the most commonly used non-invasive brain stimulation technique in the literature and involves passing a constant direct current between two electrodes placed on the scalp to either increase (anodal stimulation) or decrease (cathodal stimulation) the excitability of a specific cortical region, usually primary motor cortex (M1) (Horvath, Forte, & Carter, 2015; Stagg & Nitsche, 2011). However, anodal tDCS is primarily employed as it typically increases cortical excitability and motor

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https://doi.org/10.1016/j.humov.2019.04.017
Received 10 December 2018; Received in revised form 30 April 2019; Accepted 30 April 2019
Available online 09 May 2019
0167-9457/

function, whereas cathodal tDCS has shown opposite results or no effect on motor function (Buch et al., 2017; Stagg & Nitsche, 2011; Stagg et al., 2011). The majority of anodal tDCS studies have shown motor performance improvements of 10–15% during or shortly after a single application lasting 10–20 min when compared to practice alone (Buch et al., 2017). However, there is a need for additional development and an improved understanding of the parameters and type of stimulation that may promote motor skill acquisition and learning (Buch et al., 2017).

tRNS possesses many of the same features and methodological considerations as tDCS (Terney et al., 2008). However, there are also several important differences between the two techniques which could potentially influence behavioral and physiological outcomes. For example, the application of tDCS involves the delivery of a continuous current, whereas in tRNS the current is delivered in a random-noise fashion with the positive and negative current emanating from the same electrode (Terney et al., 2008). Most importantly, research suggests that tRNS may be able to increase cortical excitability and improve motor performance to similar or greater extents than tDCS. For example, tRNS applied to the M1 of young adults for 10 min led to a performance increase of about 10% in a serial reaction time task (sequence of finger presses) and large increases (~50–75%) in cortical excitability (Terney et al., 2008). This increase in cortical excitability is greater than the average increase of ~30% seen after tDCS (Horvath et al., 2015). In addition, the physiological mechanisms mediating these enhancements in performance and cortical excitability may differ between the two methods. Specifically, tDCS may involve the modulation of NMDA receptors (Stagg & Nitsche, 2011), as well as GABAergic (Buch et al., 2017; Stagg & Nitsche, 2011; Stagg et al., 2009) and glutamatergic synapses (Stagg & Nitsche, 2011). In contrast, tRNS may be primarily associated with repetitive, more frequent activation of sodium channels (Antal & Herrmann, 2016; Terney et al., 2008), which could underlie the observed greater increases in cortical excitability with tRNS compared to tDCS and potentially greater enhancements in motor function (Prichard et al., 2014; Terney et al., 2008). tRNS also possesses a few other potential advantages compared to tDCS such as a lack of polarity specific effects, less skin irritation, and a greater ability to blind subjects with SHAM stimulation (Terney et al., 2008).

Taken together, these behavioral and physiological effects of tRNS have important implications for enhancing performance in healthy individuals, older adults, and especially in patients with movement disorders. Accordingly, each of the six available studies that have measured the effects of tRNS on cortical excitability has found significant increases (Chaieb, Antal, & Paulus, 2015; Chaieb, Paulus, & Antal, 2011; Laczo, Antal, Rothkegel, & Paulus, 2014; Moliadze, Antal, & Paulus, 2010; Moliadze, Fritzsche, & Antal, 2014; Terney et al., 2008), whereas two of the three studies involving tRNS and motor tasks have produced performance enhancements (Saiote et al., 2013; Terney et al., 2008). Despite the promising findings of these tRNS studies, they all involved simple motor tasks such as the serial reaction time task (Terney et al., 2008), a pinch grip task (Saiote et al., 2013), and a tracing task performed with a stylus by the left hand (Prichard et al., 2014). It is currently unknown if tRNS can improve motor performance in a complex, multi-joint task involving coordination of the whole body, which would be more applicable to activities of daily living, occupational requirements, and physical activities.

The purpose of the present study was to determine the influence of tRNS on motor skill acquisition and retention in a golf putting task in young adults. Based on tRNS studies in relatively simple motor tasks (Prichard et al., 2014; Terney et al., 2008), it was hypothesized that tRNS would increase accuracy and reduce performance variability to a greater extent than practice alone in a complex golf putting task. Specifically, it was hypothesized that motor skill acquisition would be greater in the tRNS group compared to the SHAM group over the course of the practice blocks. Finally, it was expected that the degree of motor learning exhibited in the retention test would be greater in the tRNS group compared to the SHAM group.

2. Materials and methods

2.1. Participants

A total of 34 males were recruited for the study (mean age: 23.1 ± 2.8; range: 18–30 years) by means of recruitment flyers posted in buildings on campus. The primary reason we only used male participants was to possibly reduce the variability of the data. Since the task was more complex than most motor tasks done in currently available tDCS studies, it was assumed that the inter-individual variability could, at least potentially, be greater for the current task. Thus, we chose to reduce a further possible source of variability by only using men. Participants were free of any neurological disorder, psychiatric condition, and were right-handed (Laterality Quotient: mean = 77.5; range = 25–100) according to the Edinburgh Handedness Inventory (Oldfield, 1971). Potential participants who had played golf competitively or had engaged in golf or miniature golf more than one time per year were excluded from participation. Thus, all participants were novices at golf. The subjects provided written, informed consent before participating in the study. All experimental procedures were approved by the institutional review board at the University of Nevada, Las Vegas and conducted according to the Declaration of Helsinki.

2.2. Experimental design

The study was a randomized, between-subjects, SHAM-controlled, double-blind experimental design. Subjects were randomly allocated to either a tRNS or a SHAM group. Each subject participated in two experimental sessions performed on consecutive days at the same time each day. In the first session (practice session), subjects practiced the golf-putting task while receiving either tRNS or SHAM stimulation to determine the influence of the stimulation on motor skill acquisition. In the second session (retention session), subjects performed a retention test to quantify the magnitude of motor learning elicited by each of the two stimulation types given in the practice session. The practice session proceeded in the following steps: 1) viewing of an instructional video; 2) transcranial

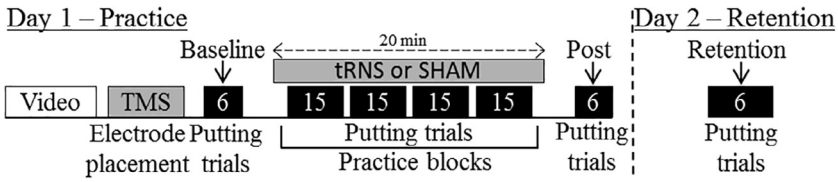

Fig. 1. Schematic representation of the experimental protocol that comprised an instructional video, FDI motor hotspot determination with TMS, a baseline test block, 4 practice blocks (performed concurrent with tRNS or SHAM), and a post test block on Day 1 (practice session), followed by a retention test block on Day 2 (retention session).

magnetic stimulation (TMS) application to identify the placement site for the tRNS electrodes; 3) a baseline test block of golf putting; 4) 4 practice blocks of golf putting trials while receiving tRNS or SHAM; and 5) a post test block of golf putting. Twenty-four hours later subjects completed the retention session, which involved one block of golf putting performed in an identical manner to the baseline and post test blocks of the previous day (Fig. 1).

2.3. Experimental procedures

2.3.1. Instructional video

Subjects watched a didactical video of an expert golfer performing the golf putting task on the same laboratory putting green as subjects performed the task during data collection. The purpose of the video was to facilitate a desirable and relatively consistent putting technique among all participants in order to reduce performance variation due to different putting techniques in the subsequent golf putting trials. This video has been included as Supplementary material.

2.3.2. TMS

Single pulse TMS was performed using a Magstim 200^2 connected to a double 70 mm remote control figure-of-eight coil to identify the motor hot spot of the first dorsal interosseous muscle (FDI) of the left hemisphere. The coil was held tangential to the scalp, orientated with the handle pointed backwards, and positioned laterally at 45 degrees from the midline over the M1 hand representation area. Subjects received approximately 20–30 pulses so that the scalp area corresponding to the FDI motor hot spot could be identified and marked with a pen for subsequent tRNS electrode placement (Karabanov et al., 2012; Poston, Kukke, Paine, Francis, & Hallett, 2012). EMG of the FDI muscle was recorded with surface electrodes arranged in a belly tendon montage.

2.3.3. tRNS application

A NeuroConn DC Stimulator Plus/MR was utilized to deliver high-frequency tRNS through two rubber electrodes (7 × 5 cm) that were encased in saline soaked sponges at a current strength of 2 mA. In this mode, the stimulator generated a random current for every sample with a sampling rate of 1280 samples/s. These tRNS parameters were found to be optimal in previous studies (Chaieb et al., 2015; Laczo et al., 2014; Prichard et al., 2014; Terney et al., 2008). For SHAM, the current was ramped up over 10 s, held at 2 mA for 30 s, and ramped down over 10 s according to standard SHAM stimulation procedures (Nitsche et al., 2008), which elicit the same scalp skin sensations without exerting any physiological effects. The stimulating electrode was centered over the previously identified FDI motor hot spot, whereas the reference electrode was placed on the contralateral supraorbital region (SO). Note that although the stimulating electrode was centered over the FDI, this commonly used electrode with its rather large size (7 × 5 cm) most certainly covered most of the motor strip, in particular the upper limb muscles due to the partial overlap and close proximity between corticomotoneuronal cell locations of finger, elbow, and shoulder muscles (Rathelot & Strick, 2009). The electrodes were held in place by rubber elastic straps and the stimulation device was placed in a small, tightly fitting backpack that did not restrict performance of the task. tRNS or SHAM was applied for 20 min during the practice blocks of the practice session.

2.3.4. Golf putting task

All subjects performed the golf putting task in an identical manner in the baseline, practice, post test, and retention blocks. Subjects stood on one end of a large custom-designed laboratory putting green that did not slope in either length or width. A red "home" circle (2.54 cm diameter) was located near the end of the putting green where the putter stood and in the center of the putting surface width-wise. A very small target circle (1 cm diameter) was located 3 m away in a straight line from the home circle. Crucially, the target was a painted red circular area of the putting green surface. Thus, the target was completely level with the putting green surface as opposed to a regulation golf hole cut into the putting green. Accordingly, subjects had to modulate the force applied to the golf ball more precisely than normal golf putting to avoid errors in extent (*y*-direction). For example, a standard putt that would normally be on target but putted with marginally excessive force would result in a large overshoot error in this task as opposed to going into the golf hole. Furthermore, the putting green was very smooth (~13 on a Stimpmeter). Collectively, the very small target size, long putting distance, lack of a golf hole, and smooth surface were all task details that were specifically selected to assure that the putting task would represent a relatively difficult motor skill and that performance would have a greater potential to continually improve over time.

All participants performed the putts with a standardized golf putter in a right-handed stance. Subjects were instructed to perform each putt as accurately as possible by attempting to place the final position of the golf ball as close to the target as possible each trial.

Subjects did not receive verbal feedback from the experimenters, but were allowed to use the visual feedback of the final position of the golf ball relative to the target following each trial to facilitate the goal of minimizing error distance on each subsequent trial. The execution and recording of a block of golf putting trials proceeded in the following steps: 1) one investigator placed a golf ball in the home circle; 2) the subject performed the putt at their convenience; 3) once the golf ball came to a stop, this position was marked by an another investigator to the nearest cm with a very small, thin, circular sticker that was numbered by trial number (1–15) and the golf ball was removed from the putting green; 4) this process was repeated for the required number of trials in each block; 5) two investigators measured the *x* and *y*-error distances of each trial and recorded these values along with the corresponding trial by inputting the data into a file on a laptop computer at the end of the trial block (e.g. during the two minute rest interval between each block of practice); and 6) the stickers were removed from the green and the process was repeated for the next block of trials.

2.3.5. Baseline test block

Baseline testing consisted of one block of 6 golf putting trials to determine the initial performance levels of the two groups of subjects. Six trials were chosen because this number was deemed sufficient for baseline data without inducing an undue influence on the performance curves during the subsequent practice blocks.

2.3.6. Practice blocks and tRNS

The practice blocks were performed in association with either tRNS or SHAM for a total practice and stimulation period of 20 min. First, the stimulator was turned on for 3 min while subjects stood quietly before performing the first block of golf putts. Second, a total of 4 blocks were performed with each block consisting of 15 self-paced golf putts followed by a 2-minute rest interval to minimize any possible influence of fatigue. Third, the stimulator was kept on after the last block of putts was completed which was (usually 1–2 min to complete the 20 min stimulation period) as most subjects took about 2 min to complete each block of trials. The experimenter who placed the electrodes and programmed the stimulator at the beginning of practice did not participate in the data collection or data analysis portions of the experiment. Accordingly, the experimenters who conducted experiments and analyzed the data were blind to the group assignment of the subjects.

2.3.7. Post test block

After the practice blocks and stimulation ended, subjects rested for 5 min before performing the post test block of 6 golf putting trials.

2.3.8. Retention test block

Twenty-four hours after completion of the practice session, subjects returned to the laboratory for the retention session and performed the retention test block (6 trials). In this session, tRNS was not used and the instructional video was not played. However, the electrodes were placed on the head in the same manner to the previous day and subjects wore the backpack with the stimulation device inside. Therefore, the task conditions remained identical to the baseline test block and post test block of the previous day.

2.4. Data analysis

The endpoint error and endpoint variance were selected as the primary dependent measures of interest and as indices of motor performance (Christou, Poston, Enoka, & Enoka, 2007; Poston et al., 2013; Poston, Christou, Enoka, & Enoka, 2010; Poston, Enoka, & Enoka, 2008a, 2008b; van Beers, Haggard, & Wolpert, 2004). The endpoint error was calculated as the shortest distance between the *x* and *y* coordinates of the center of the target circle and the final endpoint of the golf ball for each trial using the Pythagorean Theorem. Therefore, endpoint error represented the absolute distance from the target and provided an overall measure of endpoint accuracy. Similar to a previous study (Poston et al., 2013), we also quantified the constant errors in the *x* and *y* directions. However, since there was no bias for undershooting or overshooting in any direction only the endpoint error will be reported here. In contrast, endpoint variance was used to quantify within-subject performance variability. Endpoint variance was determined as the sum of the variances of the x-constant errors and y-constant errors for each block of trials. Since it is possible that a subject can have a rather consistent performance, yet be relatively far from the target on average, these measures may not always be strongly correlated and provide different motor performance information (accuracy vs variability) (Christou et al., 2007; Muller & Sternad, 2004; van Beers et al., 2004).

2.5. Statistical analysis

Separate statistical analyses were conducted on the tests blocks and the practice blocks for the dependent variables (endpoint error, endpoint variance) as only the practice blocks were done concurrent with tRNS. Accordingly, two-way ANOVAs [2 *group* (tRNS, SHAM) × 3 *test* (baseline, post, and retention)] with repeated measures on *test* were used to compare the endpoint error and endpoint variance in the test blocks. Similarly, two-way ANOVAs [2 *group* (tRNS, SHAM) × 4 *block* (1, 2, 3, and 4)] with repeated measures on *block* were used to compare the endpoint error and endpoint variance for the practice blocks. Fisher LSD post-hoc tests were used to locate differences among pairs of means when appropriate. The significance level was set at $P < 0.05$ for all statistical tests. Data are indicated as means ± standard errors in the figures and means ± standard deviations in Table 1.

Table 1
Mean (SD) of the error and variability measures during the modified golf trials.

	Baseline	Block 1	Block 2	Block 3	Block 4	Post	Retention
tRNS							
Endpoint error (cm)	60.33	41.68	39.12	36.38	40.05	39.09	54.37
	(16.60)	(8.38)	(8.73)	(8.85)	(10.43)	(15.61)	(23.15)
Endpoint variance (m^2)	47.22	25.78	22.03	19.45	21.75	25.33	38.30
	(21.46)	(12.30)	(10.96)	(10.40)	(12.16)	(17.50)	(30.01)
SHAM							
Endpoint error (cm)	59.78	47.93	40.10	38.95	38.03	39.75	47.61
	(18.91)	(17.97)	(14.92)	(9.98)	(9.37)	(16.09)	(11.44)
Endpoint variance (m^2)	57.08	31.18	22.14	20.88	19.14	20.77	29.66
	(31.40)	(19.79)	(10.14)	(10.80)	(10.85)	(15.51)	(18.44)

3. Results

3.1. Test blocks

For endpoint error, there was no main effect for *group* as the endpoint error was similar for the tRNS and SHAM groups when averaged over the three test blocks ($F[1, 32] = 0.272$, $P = 0.606$; Fig. 2A). However, there was a significant main effect for *test* ($F[2, 64] = 16.528$, $P = 0.001$) and post hoc analyses indicated that the endpoint error was greater for the baseline test block compared with the post test and retention ($P = 0.001$ and 0.012, respectively). Finally, the *group* × *test* interaction was not significant ($F[2, 64] = 0.613$, $P = 0.545$). The endpoint variance was also similar between the two groups ($F[1, 32] = 0.042$, $P = 0.839$; Fig. 2B) when averaged over the three test blocks. Conversely, there was a significant main effect for *test* ($F[2, 64] = 17.102$, $P = 0.001$), and post-hoc analyses indicated that endpoint variance was greater for the baseline test block compared to post test and retention blocks ($P = 0.001$ and $P = 0.002$, respectively). The *group* × *test* interaction was not significant ($F[2, 64] = 1.868$, $P = 0.163$).

3.2. Practice blocks

For endpoint error, there was no main effect for *group* as the endpoint error was similar for the tRNS and SHAM groups when averaged over the four blocks of practice trials ($F[1, 32] = 0.422$, $P = 0.521$; Fig. 2A). However, there was a significant effect for *block* ($F[3, 96] = 4.463$, $P = 0.006$) and post hoc analyses indicated that the endpoint error was greater for the first block of practice when compared with the second, third and fourth practice block ($P = 0.018$, 0.005, and 0.012, respectively). The *group* × *block*

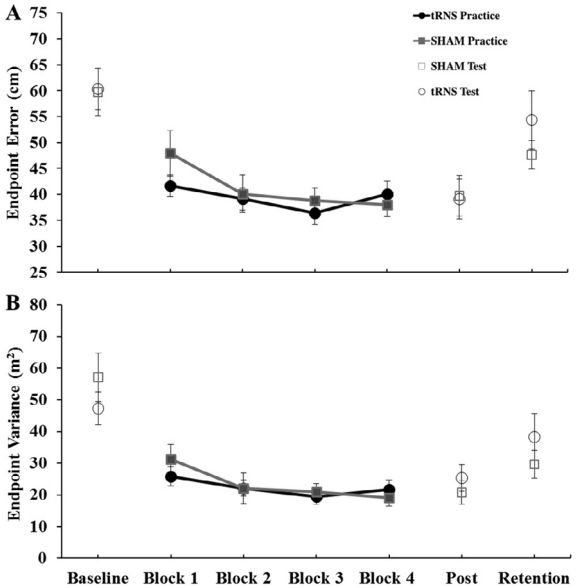

Fig. 2. Endpoint error and endpoint variance for the tRNS and SHAM groups across the practice and test blocks. Each data point corresponds to the mean ± SE for one block of trials for the tRNS group (circles) and SHAM group (squares) for the practice blocks (filled circles and squares) and the test blocks (open circles and squares). A. The endpoint error declined across the practice blocks and the test blocks, but these declines were similar for the tRNS and SHAM groups in the practice and test blocks. B. The endpoint variance error declined across the practice blocks and the test blocks, but these declines were similar for the tRNS and SHAM groups in the practice and test blocks.

interaction was not significant (F[3, 96] = 1.324, $P = 0.271$). Endpoint variance was also similar between the two groups (F[1, 32] = 0.116, $P = 0.735$; Fig. 2B) when averaged over the four blocks of practice trials. However, there was a significant main effect for *block* (F[3, 96] = 5.417, $P = 0.002$), and post-hoc analyses indicated that endpoint variance was greater for the first block of practice compared with the second, third and fourth practice blocks ($P = 0.036$, 0.004, and 0.004, respectively). The *group* × *block* interaction was not significant (F[3, 96] = 1.001, $P = 0.396$).

4. Discussion

The purpose of the study was to determine the influence of tRNS on motor skill acquisition and retention in a golf putting task in young adults. The study produced three main findings. First, golf putting accuracy improved with practice, but the magnitude of motor skill acquisition was not different between the tRNS and SHAM groups. Second, golf putting performance variability improved with practice, but the reduction in endpoint variability was also similar for the tRNS and SHAM groups. Third, tRNS did not enhance long-term motor learning of the golf putting task compared to SHAM as the retention test performances were similar for the two groups. Taken together, these findings indicate that a single session of tRNS applied to the motor cortex does not improve motor skill acquisition or motor learning in a complex movement task such as golf putting in young adults.

4.1. Influence of tRNS on motor skill acquisition and motor learning

Motor skill acquisition refers to a temporary change in motor performance observed during a practice session and immediately after practice has ceased, whereas motor learning is a relatively permanent change in motor performance measured in a retention test at some time point (usually a minimum of 24 h) following the end of a practice session (Bologna et al., 2015). Furthermore, the physiological adjustments mediating these processes over these time periods are different (Bologna et al., 2015). Accordingly, the present study quantified motor skill acquisition in a series of practice blocks and 5 min post practice along with the degree of motor learning attained in a longer-term retention test (24 h after practice). It was originally hypothesized that the tRNS group would exhibit both increased skill acquisition during practice and a greater amount of motor learning in the retention test conducted 24 h later. Contrary to this prediction, the endpoint error and endpoint variance were not statistically different for the two groups during practice nor did they differ at the end of practice or in the retention test.

The results of the current study are in contrast to two previous tRNS studies that reported that tRNS enhanced performance in a finger sequence task (Terney et al., 2008) and a handwriting tracing task (Prichard et al., 2014), but consistent with another study where tRNS failed to increase performance in a visuomotor isometric force matching task (Saiote et al., 2013). The present findings should also be considered in the context of tDCS motor skill and learning experiments. If all of the single session tDCS motor skill studies that involved M1 stimulation in young adults compiled in a recent review (Buch et al., 2017) (see their Table 1) are examined, it can be determined that about two-thirds of these approximately 25 papers have reported skill increases either during or immediately after practice. Importantly, all of these tRNS and tDCS studies involved relatively simple, unilateral motor tasks. For example, more than half of these studies utilized tasks involving one to four digits of the hand and almost all the others involved various hand-arm movements similar to activities of daily living such as handwriting and the Jebsen-Taylor Hand Function Test (Buch et al., 2017). In contrast, our results are consistent with a recent study (Vancleef, Meesen, Swinnen, & Fujiyama, 2016) that found that tDCS applied to M1 did not increase acquisition (first day) or learning (over four days) compared to SHAM in a complex bimanual tracking task involving the hand and wrist muscles. However, tDCS has improved motor function in whole body tasks like walking (Valentino et al., 2014) and dancing (Kaski, Allum, Bronstein, & Dominguez, 2014) in patients with motor disorders, though this is probably not a valid comparison as the ability of tDCS to improve motor performance scales with the age of the subjects and the level of impairment due to motor disorders as these populations have much lower baseline performances and more room for motor performance improvements.

4.2. Possible factors responsible for the lack of ability of tRNS to improve motor performance

These disparate findings between the current study and the majority (~2/3rds) of the tRNS (Prichard et al., 2014; Saiote et al., 2013; Terney et al., 2008) and acute tDCS studies on motor skill acquisition (Buch et al., 2017) suggest that caution should be applied in assuming that tDCS and tRNS almost always lead to increases in performance (Heroux, Loo, Taylor, & Gandevia, 2017; Horvath et al., 2015). In fact, accumulating evidence suggests that the degree to which these methods can increase motor skill depends on several formerly less appreciated factors (Horvath, Carter, & Forte, 2014) that are possible explanations for the lack of improvements in motor performance in the current study. First, it could be argued that the tRNS parameters of stimulation were not ideal. This is highly unlikely, however, as the present study employed the stimulation parameters for tRNS and tDCS that are considered optimal at this time with regard to the stimulation device, electrode montage and target brain area (M1-SO, electrode size), current strength, stimulation duration, SHAM protocol, use of high frequency tRNS, and stimulation concurrent with the task. Second, it is possible that the group of subjects randomly assigned to the tRNS group may have contained a relatively large number of non-responders as some evidence has shown that a non-trivial number of subjects may be non-responders to tDCS. However, these studies defined non-responders based solely on acute TMS cortical excitability measures such as resting motor threshold or the 1 mV motor evoked potential (MEP) in response to tDCS and did not measure motor performance (Labruna et al., 2016; Wiethoff, Hamada, & Rothwell, 2014). Accordingly, a recent study found that MEP increases due to tDCS were not predictive of the amount of motor learning observed (Lopez-Alonso, Cheeran, & Fernandez-del-Olmo, 2015). Most importantly, neither observation of individual subject data

nor a k-means clustering analysis provided any evidence for the tRNS group to have more responders or non-responders than the SHAM group in the current study. Finally, other factors such as level of baseline skill (Hummel et al., 2005), and time of day do not apply to the current findings as baseline skill levels were nearly identical between groups, the subject groups were young adults of the same average age within a tight age range, and the experiments for each subject were done at the same time of day.

In contrast, one more probable explanation for the lack of improvement in motor performance in the present task conditions is that a single session of tRNS may not be sufficient to significantly improve motor performance and multiple (e.g. 3–5) consecutive days of stimulation may be required. Accordingly, tRNS significantly improved performance on a tracing task performed with a stylus by the left hand compared to SHAM over three days of practice (Prichard et al., 2014). Conversely, there was a strong trend for higher tracing scores in the tRNS group by the end of Day 1, but these differences did not quite reach statistical significance. Furthermore, a tDCS group showed the exact same pattern of results relative to SHAM in that study, but there was no difference in tracing performance between the tRNS and tDCS groups (Prichard et al., 2014). However, a recent review examining all tDCS motor skill studies involving M1 simulation over multiple days (Buch et al., 2017) (see their Table 2) revealed that all six reported greater total learning after 3–5 days of tDCS. Most importantly, all but one of these studies reported an increase in motor skill on the first training day with the remaining study demonstrated a strong tendency for a skill increase due to tDCS. Thus, it appears that although tDCS usually has a cumulative positive effect on skill accrual over multiple days (Reis et al., 2009, 2013), this is far from an absolute prerequisite to be able to demonstrate performance gains due to stimulation (Buch et al., 2017).

It should also be noted that although the current study did not involve multiple days of stimulation, a retention test was performed 24 h after tRNS and practice. Of all the acute tDCS motor skill studies (Buch et al., 2017), it appears that only four of them have included a retention test the next day (Bastani & Jaberzadeh, 2014; Kang & Paik, 2011; Kantak, Mummidisetty, & Stinear, 2012; Sriraman, Oishi, & Madhavan, 2014). However, all of these were able to demonstrate improved motor learning due to tDCS in the 24 h retention test. In addition, 3–5 day tDCS studies (Cantarero et al., 2015; Reis et al., 2009, 2013) and the 3 day tRNS study (Prichard et al., 2014) have shown that significant motor skill enhancements due to the stimulation are present by the first trial block on Day 2. Taken together, these lines of reasoning suggest that the design of the present study should have been able to detect increases in performance due to tRNS if they were present, despite the lack of multi-day stimulation. Nonetheless, all of previous multi-day studies used relatively simple, unilateral hand-arm tasks so it cannot be completely ruled out that multiple day stimulation could be needed for complex movements.

Accordingly, another explanation for the present findings is that details related to the complexity of the golf putting task due to it being a whole body, bimanual task may have precluded the ability of tRNS to elicit a meaningful enhancement in performance. Strong evidence for this assertion comes from a recent study (Vancleef et al., 2016), which found that tDCS failed to improve motor performance either on the first day or over four days on a complex bimanual tracking task involving the hand and wrist muscles. In addition, the same research lab previously found that tDCS could increase motor skill on simple unilateral tasks that included finger tapping and an isometric pinch force task (Saucedo Marquez, Zhang, Swinnen, Meesen, & Wenderoth, 2013). These two sets of findings seem to reconcile the disparate results between our study and previous tRNS and tDCS studies that successfully increased motor skill in unilateral hand-arm tasks. It has been proposed that the physiological mechanism underlying these seemingly contradictory outcomes is likely that a more distributed cortical network involving relatively greater activation of several cortical regions may need to be recruited for complex bimanual skill learning (Vancleef et al., 2016). Therefore, it is possible that stimulation of one cortical region may not be sufficient to increase motor skill in complex tasks, but to our knowledge this topic has not yet been investigated. Collectively, these lines of evidence seem to indicate that the details of the current task are the most likely reason for the lack of tRNS to elicit skill improvement in the current study. Nonetheless, it is highly probable that a combination of single-day stimulation (Prichard et al., 2014) with the complex motor task both contributed to the results. Future studies that involve tRNS applied over 3–5 days in a complex bimanual task will have to be conducted to discriminate between these possible explanations.

4.3. Conclusions

In summary, subjects reduced the endpoint error and endpoint variance with practice and across testing sessions on two consecutive days, but these improvements were not different between the tRNS and SHAM groups. Thus, tRNS failed to enhance skill acquisition or motor learning in this complex, bimanual motor task that primarily involved the shoulder musculature in the experimental conditions employed in this study. When considered in the context of the existing tRNS and tDCS literature, the results of the present study suggest that tRNS may not be able to significantly improve motor skill or learning in complex bimanual tasks that involve the whole body, that it may take multiple stimulation sessions over several days for any positive effects to become evident, or that a different electrode arrangement such as a bilateral stimulation montage may be needed.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The authors would like to thank Dr. Sheniz Moonie for assistance with the cluster analysis. The author Albuquerque LL was financially supported by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2019.04.017.

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