

December 2015

The Influence Of Transcranial Random Noise Stimulation On Motor Skill Acquisition And Learning In A Modified Golf Putting Task

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THE INFLUENCE OF TRANSCRANIAL RANDOM NOISE STIMULATION ON
MOTOR SKILL ACQUISITION AND LEARNING IN A MODIFIED GOLF PUTTING
TASK

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A thesis submitted in partial fulfillment
of the requirements for the

Masters of Science – Kinesiology

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University of Nevada, Las Vegas
December 2015

Thesis Approval

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November 10, 2015

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The Influence of Transcranial Random Noise Stimulation on Motor Skill Acquisition and Learning in a Modified Golf Putting Track

is approved in partial fulfillment of the requirements for the degree of

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ABSTRACT

Transcranial random noise stimulation (tRNS) is a form of non-invasive brain stimulation (NIBS) that has been shown to increase motor performance in simple motor tasks. The purpose of the present study was to determine the influence of tRNS on motor skill acquisition and learning in a complex, modified golf putting task in young adults. Twenty-four ($n = 12$ per group) healthy young adult males were allocated to either a tRNS group or a SHAM stimulation group. Both groups performed 6 trials of the golf putting task in a baseline testing block, followed by 4 practice blocks of 15 trials. The practice blocks were followed by a post-testing block (6 trials) that was performed five minutes after the last practice block, and a retention testing block (6 trials) that was performed 24 hours later. For the practice blocks, subjects performed the golf putting task for 20 minutes in combination with either tRNS or SHAM stimulation. tRNS or SHAM stimulation was applied to the motor cortex with the stimulating electrode centered over the motor hotspot of the first dorsal interosseous muscle. The primary dependent variables were endpoint error and endpoint variance, whereas the putter face angle relative to ball path at impact and forward swing time were selected as secondary dependent variables. For the practice blocks, the dependent variables were analyzed by two-factor repeated measures ANOVAs: 2 *group* (real tRNS, SHAM) x 4 *Block*. For the testing blocks, the dependent variables were analyzed by two-factor repeated measures ANOVAs: 2 *group* (real tRNS, SHAM) x 3 *Test* (BASELINE, POST and RETENTION). The results indicated that there were no significant differences in endpoint error or endpoint variance between the tRNS and SHAM groups for the practice blocks. However, there was a significant reduction in endpoint error between blocks 1 and 3 ($P = 0.20$), and a significant reduction in endpoint variance between blocks 1 and 3, and 1 and 4 ($P = 0.011$ and 0.039 , respectively). For face angle relative to path, there was a

significant *group x block* interaction, but the post-hoc tests failed statistical significance. Forward swing time remained invariant across all of the practice blocks. For the testing blocks, endpoint error was significantly reduced in both groups between the baseline block and the post-test block ($P = 0.000$), but there was no difference between groups. Similarly, endpoint variance was not different between groups, but decreased significantly for both groups between the baseline block and the post-test block, and between the baseline block and retention block ($P = 0.000$ and 0.018 , respectively). Face angle relative to path was significantly more closed for both groups in the post-test block comparison to the baseline block ($P = 0.012$) and more opened in the retention block when compared to post-test block ($P = 0.028$). Forward swing time was not different between groups or between any of the testing blocks. These findings suggest that tRNS influenced the execution of this motor task, but this influence did not occur in a manner that lead to an improvement in motor skill acquisition or motor learning in the current task conditions.

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CHAPTER 1

INTRODUCTION

Over approximately the last decade, non-invasive electrical brain stimulation methods have been developed as interventions to improve motor performance in healthy subjects as well as a variety of patient populations. Of these methods, transcranial direct current stimulation (tDCS) currently seems to be the most promising, effective, and practical. tDCS involves passing a constant direct current between two electrodes placed on specific scalp locations to either increase or decrease the excitability of a specific brain region, usually the primary motor cortex (M1). In general, the majority of these studies have shown increases of 10-15% in motor performance after a single tDCS application lasting 10-25 minutes. These acute performance enhancements are thought to be at least partially due to the increases in cortical excitability elicited by the stimulation, since the observed excitability increases mimic those seen following motor practice. Overall, these findings are promising due to the safety, practicality, and relative ease in which non-invasive brain stimulation methods can be administered. Nonetheless, much room exists to optimize the stimulation parameters of various non-invasive electrical brain stimulation methods as only a small subset of the possible stimulation methods and parameters have been investigated.

Recently, a new form of non-invasive electrical brain stimulation termed transcranial random noise stimulation (tRNS) has been developed. tRNS shares many of the same characteristics and methodological considerations as tDCS except that the current is not sent continuously, but in a random noise fashion with the positive and negative current coming from the same electrode (25). Most importantly, some research has implied that tRNS may be able to improve performance and increase cortical excitability to similar or greater extents than tDCS (4,9,15,21,25). For example, TRNS applied for 10 minutes to M1 of young adults

led to an approximate 10% decrease in reaction time and large increases (~ 50%) in cortical excitability (25). This magnitude of increase in cortical excitability is generally greater than those seen after tDCS application. In addition, the underlying physiological mechanisms mediating these enhancements in performance and cortical excitability may differ between the two methods (4,9,15,21,25). Specifically, tRNS may lead to repeated, more frequent opening of sodium channels than tDCS. In theory, this could lead to greater increases excitability, and therefore, in performance after a single application (4,9,21,25) or over a chronic (multiple days) stimulation paradigm (15) compared to tDCS. Taken together, these behavioral and physiological effects of tRNS would have important implications for enhancing performance in healthy individuals, older adults, and especially in patients with movement disorders.

Purpose of Study

At the present time, six studies have investigated the influence of tRNS on motor performance and/or cortical excitability compared to at least several hundred studies on tDCS. Despite the promising findings of these preliminary tRNS investigations, these studies have only investigated simple motor tasks such as reaction time, pinching, and tracing. Therefore, it is currently unknown if tRNS can improve motor performance on a complex, multi-joint task involving the whole body. Based on this limitation, the purpose of the present study was to determine the influence of tRNS on motor skill acquisition and learning in a modified golf putting task in young adults. This will be accomplished by having two groups of subjects perform a large series of golf putts in a practice session while either real tRNS or SHAM stimulation is applied to M1, followed by a retention session 24 hours later involving follow up testing of golf putting performance. Thus, the practice session will quantify motor

skill acquisition, whereas the retention session will quantify the amount of motor learning that occurred.

Research Hypotheses

Hypothesis 1

H₀₁: tRNS will have no effect on both accuracy and variability in a modified golf putting task.

H_{A1}: tRNS will improve accuracy and lower variability in a modified golf putting task.

Hypothesis 2

H₀₂: tRNS will have no effect on both putter face angle relative to path and forward swing time in a modified golf putting task.

H_{A2}: tRNS will improve putter face angle relative to the path and forward swing time in a modified golf putting task.

CHAPTER 2

REVIEW OF RELATED LITERATURE

Non-invasive Brain Stimulation Overview

Existing forms of non-invasive brain stimulation (NIBS) can be used in research studies for basic science purposes, as interventions to improve motor performance, and as diagnostic tools to measure specific inhibitory and excitatory neural pathways. Transcranial magnetic stimulation (TMS) has been the most widely studied non-invasive brain stimulation technique and can be used for all of the aforementioned purposes depending on the mode employed (10). TMS involves applying brief magnetic pulses in to the scalp, which when given at a sufficient intensity induces action potentials in a large numbers of cortical neurons. TMS exists in three basic modes: single pulse, paired pulse, and repetitive (rTMS). Single pulse is used to measure cortical excitability, whereas paired pulse is used to measure specific inhibitory and excitatory cortical pathways. Therefore, these two forms are used as basic tools to study and diagnose physiological function. In contrast, rTMS is used as an intervention to increase or decrease excitability of a targeted brain region to modify motor or cognitive performance. In general, rTMS involves many pulses given in a short period of time and it increases cortical excitability when stimulation frequency is higher than 5 Hz and decreases cortical excitability when the frequency is 1 Hz or below (8).

For intervention purposes, however, tDCS is now becoming the non-invasive brain stimulation method of choice as it is more effective, safe, cost effective, and easier to use than rTMS. In motor system studies, M1 is the most frequently targeted brain area and the majority of research studies have shown enhanced performance in a variety of different populations when this area is stimulated with tDCS. Most importantly, tDCS elicits these

effects in an extremely safe manner when the stimulation parameters are applied according to international guidelines and range. As opposed to TMS, neuronal action potentials are not elicited directly by tDCS. Instead, tDCS modulates cortical excitability by depolarizing or hyperpolarizing the resting membrane potential of neurons, which may ultimately decrease or increase the spontaneous firing rates of specific neuronal populations (11). More recently, a variation of tDCS called tRNS has been developed and a few initial studies have been conducted. The main difference between tDCS and tRNS is that in tRNS the current is not passed continuously, but in a random noise fashion with the positive and negative current emanating from the same electrode (25). The net result of this arrangement, according to Terney et al. (2008), is that tRNS may promote increased excitability through different mechanisms at the cell membrane level compared to tDCS.

History of tDCS

The first recorded experiment that involved passing an electrical current through the scalp has been reported to have occurred around 43-48 AD. A patient with a headache had the symptoms relieved after a live torpedo fish was placed on the scalp by a physician named Scribonius Largus (16). Later in 131-401 AD, these findings were replicated by Pliny the Elder and the Greek physician Claudius Galen. Subsequently, over a thousand years later, electrical brain stimulation was reintroduced by Walsh in 1773 who applied modern scientific methods to further investigate the application of electric torpedo fish in clinical medicine, which helped contribute to the development of electrophysiological science. Walsh findings influenced two Italian scientists, Galvani and Volta, who lately found that different stimulation durations could lead to different physiological responses. Consequently, clinical medicine started to implement galvanic direct current as a treatment for mental disorders

(melancholia and depression) around 1804. However, galvanic direct current produced contradictory findings that led to its cessation in the medical field after the electroconvulsive therapy was created. The modern era of electrical brain stimulation began about 50 years ago when scientists started showing renewed interest towards determining weakest current intensity capable of altering brain excitability (16). The majority of the findings indicated that anodal currents led to enhanced alertness, mood, and motor activity compared to quietness and apathy elicited by cathodal stimulation. Similarly, animal studies in the 1950's demonstrated that anodal stimulation increased neuronal firing rates, while cathodal stimulation had the opposite effect. However, these studies were not performed in humans as the currently used methods functional magnetic resonance imaging (fMRI) and TMS to study human brain function in response to direct current stimulation had not yet been invented. This situation changed in the mid-1980's with the invention of TMS and the development of advanced fMRI technology. Thus, tDCS started to be studied as an intervention to improve human motor and cognitive performance approximately 10 years ago in studies that employed TMS and/or fMRI in conjunction with tDCS.

tRNS Overview

tRNS is a newer NIBS mode that could be viewed as a variation of tDCS due to the similar overall application and methodological procedures used in both techniques. However, tRNS has recently been shown to enhance cortical excitability through slightly different mechanisms than tDCS. Based on these different mechanisms of action and the limited available research studies, some researchers have suggested that tRNS may promote similar or better therapeutic effects and fewer disadvantages as opposed to tDCS. For example, tDCS may have a greater propensity to cause skin irritation (12,15,21,25) and effective blinding of

subjects is slightly more difficult during application of SHAM stimulation. Additionally, tRNS differs from tDCS in that the applied current has an oscillatory nature, which tends to increase cortical excitability without the polarity-dependent current characteristic of tDCS, where anodal tDCS increases and cathodal tDCS decreases cortical excitability (3).

To date, six studies have investigated the effects of tRNS on M1 (4,7,9,15,21,25) and four of these utilized the same stimulation protocol. In addition, the most recent tRNS studies have investigated a new tRNS protocol that employs a DC offset (4,7). According to Terney et al. (2008), this essentially involves generation of a set of random numbers that are normally distributed with a probability density function that follows a bell-shaped curve. Additionally, in the frequency spectrum all coefficients have a similar size known as "white noise." The noise signal contains all frequencies up to half of the sampling rate (i.e. a maximum of 640 Hz) when set to the highest frequency rate.

Two frequency spectrums can be used: a low frequency spectrum from 0.1 to 100Hz, and a high frequency spectrum from 101 to 640Hz. In the two studies that utilized the low frequency spectrum there was no excitatory effect on the M1 (25) and a tendency to deteriorate learning (21). On the other hand, several studies that applied the high frequency spectrum, either found a significant excitatory effect when compared to SHAM or improvements in motor performance (9,15,25). However, one study found no significant improvement in motor learning (21).

The physiological mechanisms underlying these tRNS effects have received far less study than the behavior outcomes. However, based on current evidence it has been suggested by Terney et al. (2008) that tRNS may lead to a continuous opening in sodium channels, which could lead to enhanced membrane depolarization. In contrast, Terney et al. (2008) speculated that tDCS may only open sodium channels once, which may not generate as great of flux of ions and, therefore excitability may not be enhanced to the extent of tRNS effects.

Regardless of the exact mechanisms, it is possible to conclude at the present time based on available research that tRNS may elicit a higher increase in excitability when compared to tDCS along with better performance and motor learning in a simple motor task when compared to SHAM stimulation. Finally, besides different mechanism of actions, tRNS has been shown to have a higher threshold for skin sensation and itching compared with tDCS. For instance, the 50% threshold for skin sensation occurs when tDCS is set at 400 μ A, as opposed to 1200 μ A when utilizing tRNS, resulting in a more effective blinding procedure for research and intervention purposes (1).

The Effect of tRNS on Motor Learning and Performance

The first study analyzing cortical excitability and motor performance after tRNS stimulation of M1 utilized a between-subjects design to compare behavioral and electrophysiological outcomes between high frequency tRNS, low frequency tRNS and SHAM stimulation (25). Healthy young subjects performed a serial reaction time task (SRTT), which involves producing a specific sequence of button pushes by performing finger flexions with the index, middle, ring, and pinky finger of one hand. Cortical excitability was measured by motor evoked potentials (MEP) of the first dorsal interosseus muscle (FDI), which were recorded before and following stimulation of its motor-cortical representation field by single-pulse TMS. Moreover, a range of electrophysiological variables were measured by single-pulse TMS and included resting motor threshold (RMT), active motor threshold (AMT), 1 mV peak-to-peak amplitude (SI1mV), and the cortical silent period. Additionally, a smaller cohort of subjects had the short-interval intracortical inhibition (SICI)/intracortical facilitation (ICF), long-interval intracortical inhibition (LICI), and recruitment curves measured by paired-pulse TMS. tRNS was applied for 10 minutes with a

current strength of 1 mA and a maximal current density of $62.5 \mu\text{A}/\text{cm}^2$ over the M1, which is below the safety parameters accepted for tDCS (25).

The main finding of this study was a 20-50% increase in cortical excitability when high frequency tRNS was applied and this effect lasted for 60 minutes. Conversely, there was no significant difference between RMT, AMT and SII mV for the three stimulation conditions. Additionally, as previously mentioned, low frequency tRNS application generated no effect on cortical excitability. Furthermore, for control and comparison purposes, 10 individuals received tRNS on the premotor cortex, which presented no increase in corticospinal excitability. Thus, the authors suggested that tRNS enhances corticospinal excitability when given to M1 but not premotor cortex. Moreover, individuals who were tested for the paired-pulse study showed enhanced ICF, which was likely the primary pathway responsible for the general increase in excitability (amplitude of the MEP). Finally, The hf-tRNS group also performed significantly better at the SRTT test when compared to SHAM and the lf-tRNS group, implying a more effective implicit learning with reaction time shortening during the task.

In another study, Saiote et al. (2013) investigated the influence of anodal tDCS, cathodal tDCS, low frequency tRNS, high frequency tRNS, and SHAM stimulation on a visuomotor learning paradigm. Additionally, fMRI was utilized to assess brain activity during stimulation application and visuomotor task performance. A between-subjects design was utilized with 10 individuals randomly assigned to each stimulation group. Subjects underwent the same tRNS protocol as Terney et al., 2008 and all the conditions employed the same stimulation duration.

For the visuomotor learning task, subjects wore LCD goggles and they viewed two different columns on a computer screen. The right column had a specific set height that needed to be mimicked by the left column by pressing an air-filled rubber ball equipped with

a sensor, which converted pressure changes into digital signals. Moreover, feedback was received from color-coded column heights, where green meant desired column height and red undesired. All groups of subjects performed 3 blocks of 50 trials for the task. Tracking error was quantified by the difference between the required and the applied pressure (21).

The results indicated that there were no significant differences in the visuomotor task between any of the 5 groups tested. However, there were changes in brain activity in the motor task-related network measured by fMRI for the different stimulations. For instance, when compared to SHAM, hf-tRNS decreased motor task-related activity in the left frontal cortex. Moreover, hf-tRNS had lower brain activity in the left frontal cortex, precuneus and right frontal cortex when compared to lf-tRNS. Finally, there was no difference in brain activity between tDCS and tRNS groups (21). Thus, it appears that subjects exhibited the same overall performance despite subtle differences in brain activation elicited by the various types of stimulation. This implies that these differences may not have been substantial or important enough to actually impact motor performance and be functionally significant.

Prichard et al. (2014) investigated the effect of tRNS and two montages of tDCS on learning a tracing task in healthy, right-handed individuals. Participants performed a tracing task with their non-dominant (left) hand. The task consisted of three to five letter words, and two seconds were given to trace each letter or shape letter on a digitizer tablet, and a time bar was shown on the screen. Further, after completing the first block, tRNS, tDCS, or SHAM stimulation was turned on for 20 minutes and training continued until a total of 12 blocks of 15 trials with a 15 second interval between blocks was finished. The experiment was repeated at the same time on three consecutive days, and the third day had no brain stimulation.

The stimulation protocol was the same as previous studies (21,25), except for a 10 minutes longer duration, and side of M1 that was stimulated. For instance, the non-dominant, the right side of M1 was stimulated to investigate possible effects of the different stimulation

modes on learning a tracing task with the non-dominant hand. Additionally, tDCS had a unilateral M1 montage with a cathodal electrode placed on the contra-lateral orbit and a bilateral montage with a cathodal electrode placed on the left M1.

Acutely, there was a significant difference between groups, post-hoc *t*-tests indicated that unilateral tDCS increased performance when compared to SHAM. There was also a significant difference between unilateral tDCS and tRNS on immediate effects. On the other hand, there was no significant difference on the last day, indicating no carry on excitability on the day after stimulation, or further learning from the experimental groups.

Prichard et al. (2014) suggested that the task used for his study is more similar to the visuomotor task utilized by Saiote et al. (2013), involving synergistic and continuous movements of multiple hand and arm muscles along with hand-eye coordination. At the present time, this is the only single study that has concurrently analyzed skill learning over multiple days of both tRNS and tDCS. Moreover, Prichard et al. (2014) concluded that both tDCS and tRNS were similarly effective at improving motor learning. Conversely, a large immediate effect after unilateral tDCS was never observed.

Another study compared cortical excitability (MEP amplitude) between anodal tDCS, tRNS, theta burst stimulation (iTBS; a form of rTMS) and SHAM using a within-subjects design. Moliadze et al. (2014) emphasized that this is the only study to analyze individuals' variation between the most commonly utilized NIBS. Twelve healthy subjects were included in the study and each of them was tested in all four conditions in a counterbalanced manner, separated by at least 5 days.

The main finding was that tDCS and tRNS increased excitability as previously hypothesized (9). Furthermore, all three stimulation paradigms augmented the MEP when compared to SHAM and thus no significant difference was found between the three stimulation types. However, tRNS presented the largest MEP increase, and anodal tDCS

presented the longest duration of MEP increase. Specifically, after 60 minutes, MEP dropped to baseline values when individuals were stimulated by tRNS, as opposed to an ongoing excitability of 90 minutes when stimulated by tDCS.

Laczó et al. (2014) compared the effects of tRNS, anodal tDCS, cathodal tDCS, and SHAM when applied over the leg area of M1. The MEP of the tibialis anterior muscle was taken prior to stimulation onset and every 10 minutes after the stimulation ceased for up to a 90 minutes time point. Thus, this study used a leg muscle as opposed to a hand muscle, but the stimulation duration and intensity were similar to previous tDCS and tRNS studies. Ten healthy participants underwent 10 minutes of stimulation at 2mA intensity. The findings revealed that both tRNS and tDCS significantly increased cortical excitability of the leg area to a similar extent. More specifically, immediately after stimulation, tRNS increased excitability by 70%, which this highest value being reaching at the 30 minutes data point after stimulation. On the other hand, cortical excitability was increased gradually by tDCS after stimulation was ceased with the maximum increase of 90% compared to baseline was found at the 60 minutes data point. Moreover, increases in excitability lasted longer after anodal tDCS, with 90-minute duration, as opposed to a 40-minute duration after hf-tRNS.

Taken together, the major results of these 6 available studies that involved tRNS and motor performance can be summarized as follows: 1) tRNS usually elicits large increases in cortical excitability; 2) the increases in excitability elicited by tRNS are usually larger than tDCS and other forms of NIBS; 3) the acute increases in excitability last 40-60 minutes after the stimulation has ended, which is typically of a shorter duration than the excitability increases elicited by tDCS, which often last up to 90 minutes; 4) the increases in cortical excitability are often accompanied by increases in motor performance of hand and arm tasks (4 out of 5 studies) and the increases in excitability may be at least partially responsible for the performance increases; and 5) tRNS may also have a few less important, but significant,

positive effects such as attenuated skin sensations and a better ability to blind subjects to the stimulation condition compared with other NIBS techniques. Thus, tRNS has substantial effects on cortical excitability, and therefore at least the potential to improve motor performance to a greater extent than practice alone and compared to other NIBS techniques. However, one major limitation of current tRNS motor system studies is that they have all involved relatively simple motor tasks that were novel to the subject. Therefore, it is unknown if tRNS can improve complex multi-joint/whole body tasks, especially ones that are well-learned or familiar to the subjects.

CHAPTER 3

METHODOLOGY

Participant Characteristics

A total of 24 male and students were recruited for the study (ages range: 18-30). Participants were free of any neurological disorder, psychiatric condition, and right handed according to the Edinburgh Handedness Inventory. Potential participants who regularly engage in golf or miniature golf were excluded from participation. Thus, all participants were novices at golf.

Experimental Design

The study was a randomized, placebo-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. In the first session (practice session), subjects practiced a golf-putting task in association with either tRNS or SHAM stimulation. In the second session (retention session), subjects performed a retention test to quantify the magnitude of motor learning elicited by the two types of stimulation given in the practice session.

Experimental Procedures

Modified Golf Putting Task. All subjects performed the modified golf putting task in an identical manner in baseline, practice, and retention blocks (described below). Subjects were asked to stand on one end of a custom-designed laboratory putting green behind a line located 3 meters away from the center of a target location. The target location was a representation of a standard golf hole with a 108mm (4.5 inches) diameter. The putting workspace involved a large flat carpet with a SamPutt Lab (an ultrasound capture device; described below) located on one side of the putting green that will measure the putter and ball movement. The area around the target position was marked as a grid with Cartesian coordinates denoted for later quantification of performance. All participants performed the putts with a standardized golf putter and subjects were instructed to perform each putt as accurately as possible (endeavor to place the final endpoint of the golf ball as close to the target as possible on each trial). Subjects did not receive verbal feedback from the experimenters, but were provided with visual feedback of their putt following each putt. The modified golf putting task consisted of performing a basic golf putt, however, there was no actual hole to putt the ball, and therefore, the main goal of the task was to adjust the force of the putt to make the ball stop as close as possible to the center of the target.

Experimental Sessions. Each subject participated in a practice session followed by a retention session on consecutive days. The practice session proceeded in the following steps: 1) administration of consent form; 2) administration of Edinburgh handedness Inventory; 3) viewing of an instructional video; 4) TMS testing to identify stimulation area and tRNS electrode placement; 5) baseline testing; 6) golf putting task (4 blocks of 15 trials over a time course of 20 minutes) in association with tRNS or SHAM (practice blocks); 6) post-practice testing 7) retention testing.

Instructional video. Subjects watched a didactical video of an expert performing a short distance golf putting. The purpose of the video was to facilitate and assure a desirable form and pattern for the movement trials among all participants in order to reduce performance variation due to different techniques.

TMS testing. Single pulse TMS was used at to identify stimulation area and tRNS electrode placement. For application of TMS, the coil was held on the scalp over the M1 representation area by one of the investigators. Subjects received approximately 20-30 pulses so that the area of the scalp overlying the hand area and first dorsal interosseous motor area in M1 could be identified. Surface EMG was placed on an index finger muscle (first dorsal interosseous) during this testing and was used to quantify the activity of index finger muscle in response to TMS to identify its position on the scalp. The tRNS stimulating electrode was then be centered over the first dorsal interosseous motor area on the scalp and the reference electrode was placed over the contralateral eyebrow.

tRNS application and electrode placement. A battery-driven electrical stimulator (NeuroConn DC Stimulator Plus/MR) was utilized to deliver high-frequency tRNS through two rubber electrodes (7 x 5cm) encased in saline soaked sponges. The stimulator was set on “noise HF” mode to generate a random current for every sample with a sampling rate of 1280 samples/s. Only high frequency noise was used because previous studies reported detrimental effects elicited by low frequency stimulation. For the SHAM group, current was ramped up and down over 30 seconds according to standard SHAM stimulation procedures. The stimulating electrode was placed over the "motor hot spot" of the first dorsal interosseus of each subject's left primary M1 as determined by TMS. The reference electrode was placed on the contralateral orbit. 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.

SamPutt Lab System: SAM PuttLab is a portable motion analysis and training system that uses ultra sound measurements to accurately quantify and analyze a range of putting stroke variables. The SamPutt Lab was used to quantify the putter club face angle relative to the initial ball path at the impact and the forward swing time for each trial in both experimental sessions. These two variables were chosen as they are the two variables measured by the SamPutt system that have the highest predictive value of putting performance.

Baseline testing. Baseline testing consisted of one block of six trials to determine that both groups will start from similar performance levels. Six trials were chosen because this number is deemed sufficient for baseline data without inducing an undue influence on the performance curves during the subsequent practice blocks.

Practice blocks and tRNS. The practice blocks involving golf putting were performed in association with either tRNS or SHAM stimulation for a total practice and stimulation period of 20 minutes. A total of 4 blocks were performed with each block consisting of 15 self-paced putts followed by a 2-minute rest interval. Following each trial, a mark was made at the final ball position on the carpet and this position will be recorded online by one of the investigators, and the ball will be removed from the putting surface.

Post-practice testing. After the practice blocks, subjects had the electrodes taken off and rested for 5 minutes. Afterwards, one block of six trials was performed.

Retention testing session. Approximately 24 hours after completion of the practice testing session, subjects returned to the laboratory to perform a retention testing block (that occurred in the same manner as the baseline block. In this session, tRNS was not used and the instructional video was not be played. However, subjects were reminded to perform the task as they did on the previous day.

Data Analysis

Endpoint error and endpoint variance. The endpoint error and endpoint variance were selected as the primary dependent measures of interest and as indices of motor performance. The endpoint error was calculated as the shortest distance between the x and y coordinates of the center of the target circle (putting hole) and the final endpoint of the golf ball for each trial using the Pythagorean Theorem. Therefore, endpoint error represents the absolute distance from the target and provided an overall measure of endpoint accuracy (2,13,14,20,22). In contrast, endpoint variance measures within-subject performance variability. Since it is possible that a subject can have a relative consistent performance yet be relatively far from the target on average, endpoint error and endpoint variance are often not strongly correlated and provide different performance information. Endpoint variance was determined as the sum of the variances of the x -constant errors and y -constant errors for a given block of trials.

Putter face angle relative to ball path at impact and forward swing time. These two variables served as the secondary dependent measures and as kinematic indices of a block of strokes. The putter face angle relative to ball path is the representation of face angle relative to the path at the moment of the impact, with the best value being 0° , indicative that the ball will initially follow a straight track. Forward swing time was calculated as the time the club initiated the forward swing phase immediately after the backswing ended to the time point that the putter face hit the ball. A forward swing time duration of 800-900 ms is desired range for some professional golf tournaments.

Statistical Analysis

Practice: Endpoint error and endpoint variance (primary outcome measures) were analyzed by two-factor repeated measures ANOVAs: 2 *group* (real tRNS, SHAM) x 4 *Block*.

Similarly, putter face angle relative to ball path and forward swing time were analyzed by two-factor repeated measures ANOVAs: 2 *group* (real tRNS, SHAM) x 4 *Block*.

Retention: Endpoint error and endpoint variance were analyzed by two-factor repeated measures ANOVAs: 2 *group* (real tRNS, SHAM) x 3 *Test* (PRE, POST and Retention).

Similarly, putter face angle relative to ball path and forward swing time were analyzed with the same tests.

CHAPTER 4

RESULTS

Practice

The endpoint error was similar for the tRNS and SHAM groups when averaged over the four blocks of practice trials ($P = 0.339$). However, there was a significant effect for *block* ($P = 0.003$) and post hoc analysis indicated that the endpoint error was greater for the first block of practice trials compared to the third block of practice trials ($P = 0.20$), all other pairwise comparisons between practice trial blocks just failed statistical significance. Finally, the *group x block* interaction was not significant ($P = 0.633$), which indicated that the reduction in endpoint error across practice blocks was similar for both stimulation groups.

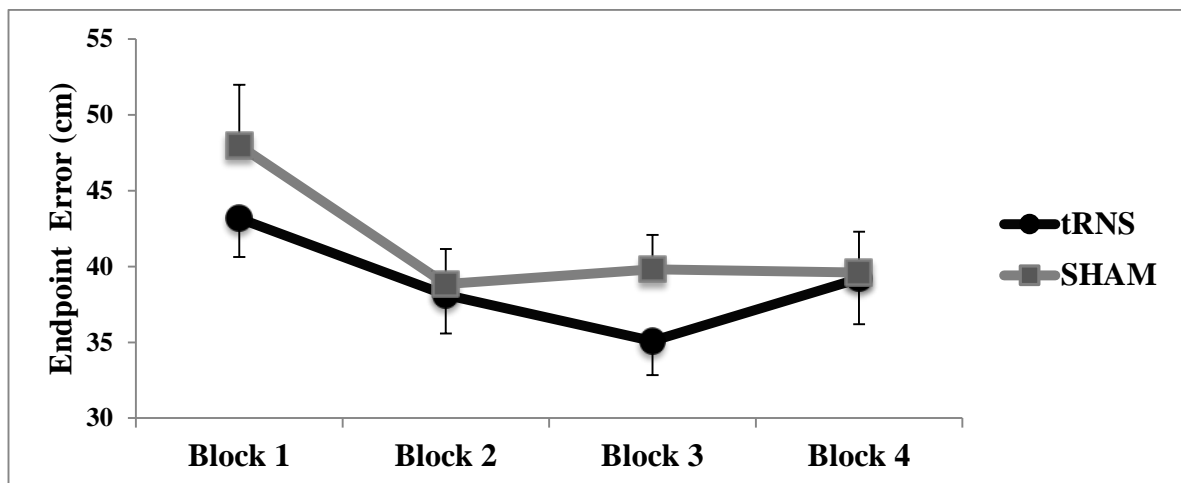


Figure 1. Endpoint error across practice blocks

Endpoint variance was also similar between the two groups ($P = 0.264$) when averaged over the four blocks of practice trials. There was also a significant main effect for *block* ($P =$

0.001), and post-hoc analysis indicated that endpoint variance was greater for the first compared with the third and fourth practice trial blocks ($P = 0.011$ and 0.039 , respectively). Lastly, the *group x block* interaction was not significant ($P = 0.612$), which indicated that the rate of reduction in endpoint variance across practice blocks was similar for both stimulation groups.

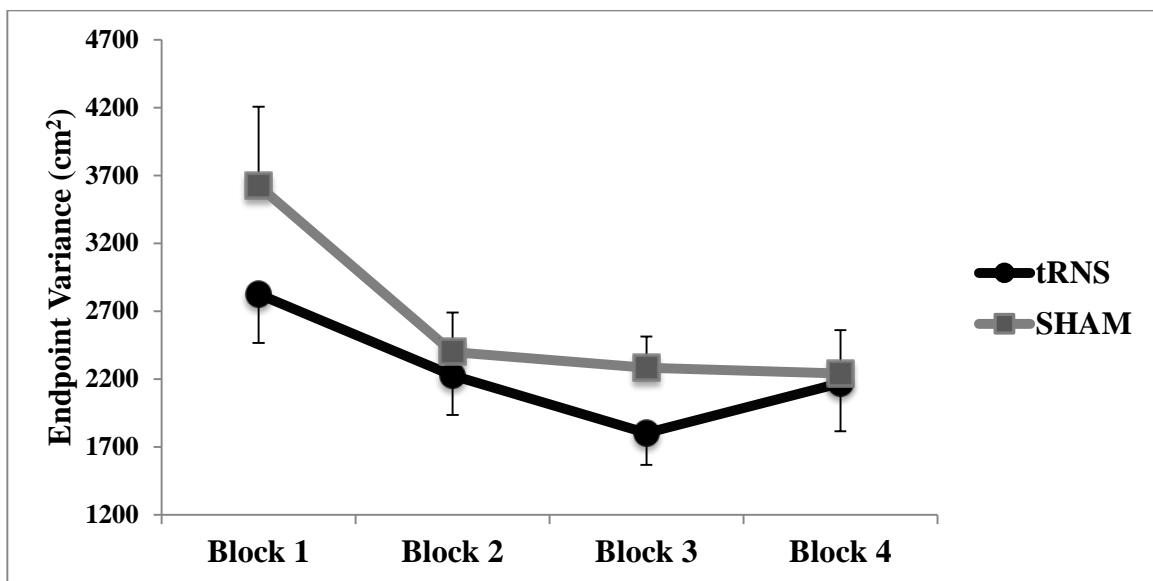


Figure 2. Endpoint variance across practice blocks

There was a significant *group x block* interaction for the face angle relative to path ($P = 0.022$), however, post hoc analysis of the interaction just failed statistical significance on Block 4 ($P = 0.053$). In addition, the main effect for *group* was not significant ($P = 0.487$). Similarly, the main effect for *block* was not significant ($P = 0.600$).

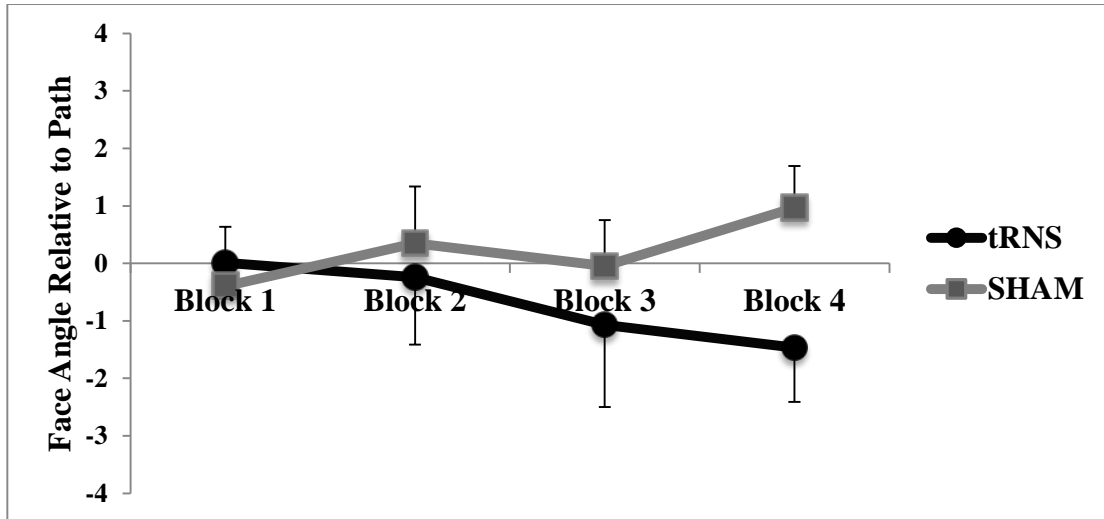


Figure 3. Face angle relative to path across practice blocks

For forward swing time, both the main effect for *group* and *block* were not significant ($P = 0.888$ and 0.152 respectively). Additionally, the *group* \times *block* interaction was not significant ($P = 0.402$), which indicated that both groups improved forward swing time at a similar rate.

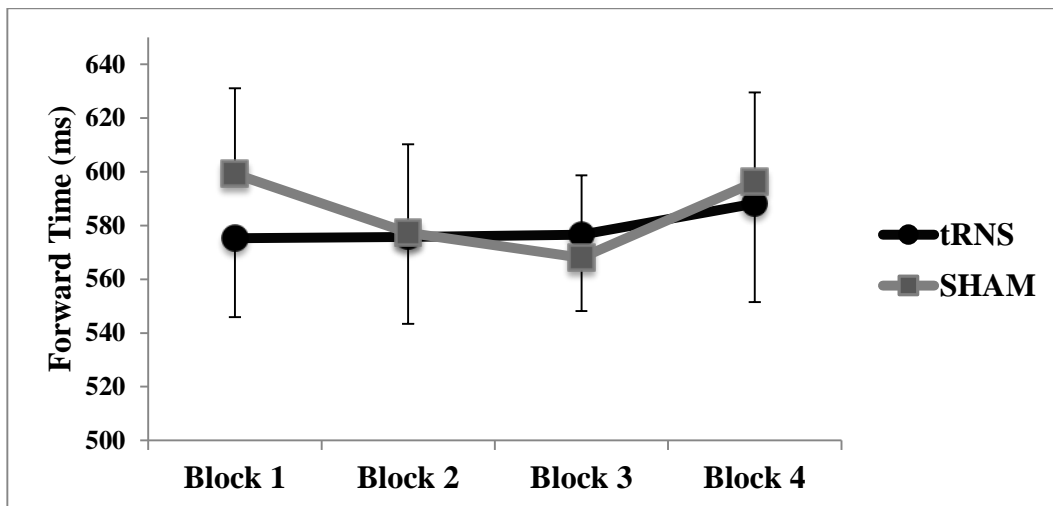


Figure 4. Forward time across practice blocks

Retention

The endpoint error was similar for the tRNS and SHAM groups when averaged over the three testing sessions ($P = 0.354$). However, there was a significant main effect for *test* ($P = 0.001$) and post hoc analysis indicated that the endpoint error was greater for the baseline testing block compared to post-practice testing block ($P = 0.000$). Finally, the *group x test* interaction was not significant ($P = 0.618$), which indicated that the reduction in endpoint error across testing blocks was similar for both stimulation groups.

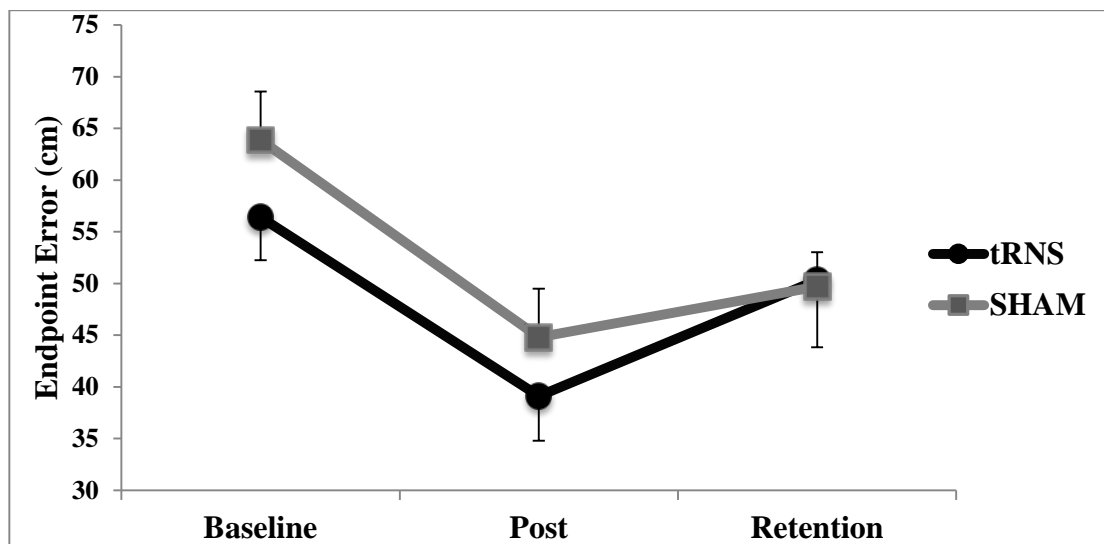


Figure 5. Endpoint error and testing blocks

Endpoint variance was also similar between the two groups ($P = 0.487$) when averaged over the three testing sessions. There was also a significant main effect for *block* ($P = 0.001$), and post-hoc analysis indicated that endpoint variance was greater for the baseline testing block compared to post-practice testing and retention blocks ($P = 0.000$ and 0.018 , respectively).

Lastly, the *group x block* interaction was not significant ($P = 0.612$), which indicated that the rate of reduction in endpoint variance across testing sessions was similar for both stimulation groups.

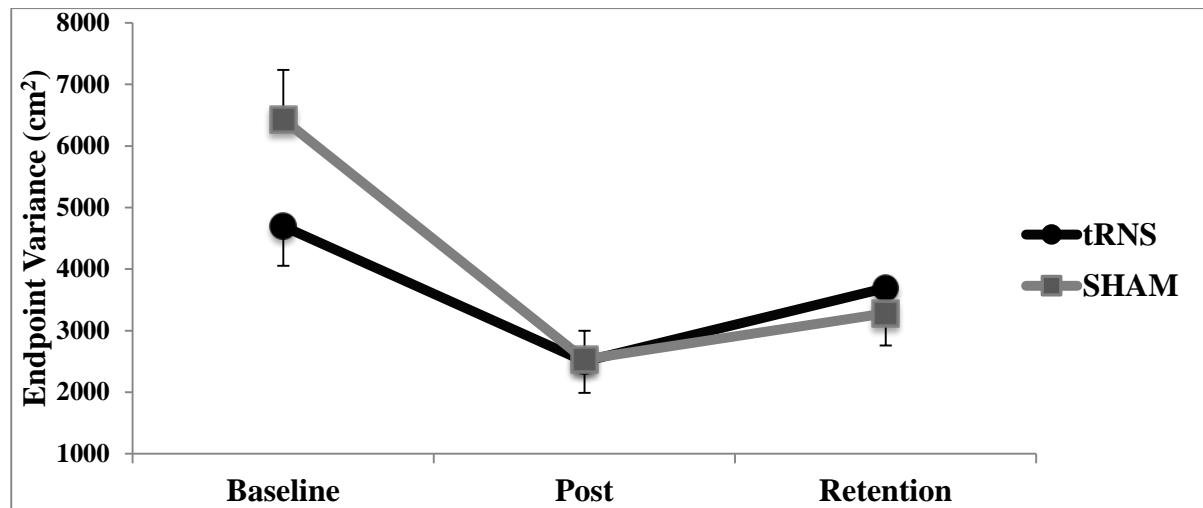


Figure 6. Endpoint variance and testing blocks

The face angle relative to path was similar for the tRNS and SHAM groups when averaged over the three testing sessions ($P = 0.691$). However, there was a significant main effect for *test* ($P = 0.005$) and post hoc analysis indicated that the face angle relative to path was more closed for the post-practice testing compared to baseline ($P = 0.012$) and more opened for the retention when compared to post-practice testing block ($P = 0.028$). Finally, the *group x test* interaction was not significant ($P = 0.863$), which indicated that the face angle relative to path across testing blocks was similar for both stimulation groups.

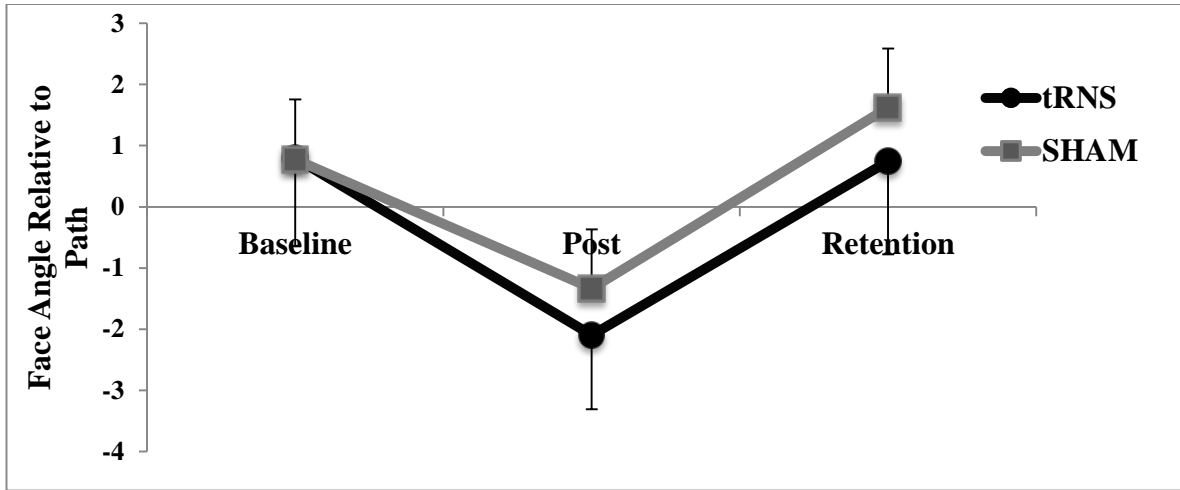


Figure 7. Face angle relative to path and testing sessions

For forward swing time, both the main effect for *group* and *test* were not significant ($P = 0.341$ and 0.340 respectively). Finally, the *group* x *test* interaction was not significant ($P = 0.290$), which indicated that both groups improved forward swing time similarly.

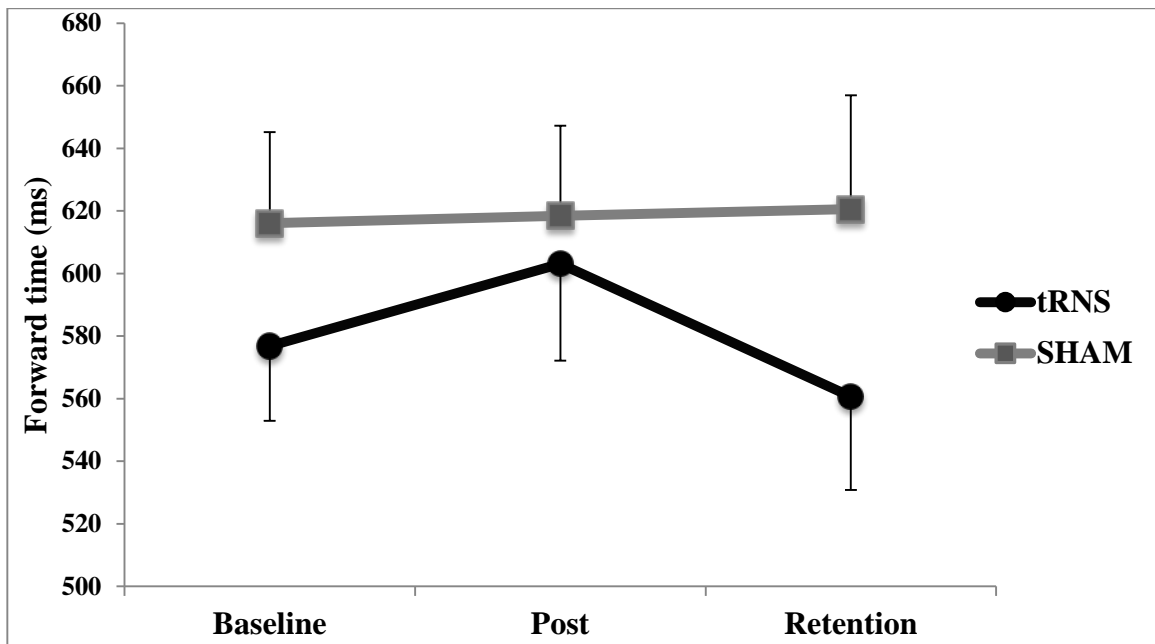


Figure 8. Forward time and testing sessions

CHAPTER 5

DISCUSSION

The purpose of the study was to determine the influence of tRNS on motor skill acquisition and learning in a modified golf putting task in young adults. The study produced four main findings. First, golf putting accuracy improved with practice, but the rate of motor skill acquisition was not different between the tRNS and SHAM groups. Second, the variability of golf putting performance improved with practice, but the rate of reduction in endpoint variability was similar for the tRNS and SHAM groups. Third, tRNS did not enhance either immediate or long-term retention of the golf putting task compared to SHAM. Fourth, there was a strong trend for the face angle of the putter to become more closed for the tRNS group as the practice and stimulation period progressed, which could have been due to the impact of the stimulation on the magnitude or direction of the grip forces of the right hand. 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 golf putting task in young adults.

tRNS and Motor Skill Acquisition During Practice

Previous studies that have applied tRNS to the motor cortex of young adults have found that tRNS increased cortical excitability and improved motor performance in a serial reaction time task (25) and in a handwriting task (15). Specifically, all three tRNS studies that have measured cortical excitability have found that high frequency tRNS increased MEP amplitude (4,7,25), whereas two of three studies that involved performance of a motor task found increases in performance following tRNS application (15,25). However, one limitation

of these studies is that they examined relatively simple motor tasks. Therefore, the present study was designed to determine if application of tRNS could improve motor performance in a complex, multi-joint task that required the coordination of many muscles to simultaneously produce the movement and to prevent undesired movements. This was accomplished by employing a difficult modified golf putting task. A golf putting task was chosen because this task has been used extensively in numerous previous motor learning studies and represents a relevant, real world motor task that is of interest to scientists interested in practical applications as well as those more concerned with basic motor control mechanisms underlying the performance of complex motor tasks.

The primary measure of task performance in the present study was endpoint error, which is the most commonly accepted metric of the final positional accuracy of goal-directed movements (13). Thus, subjects were given explicit instructions to try to minimize their endpoint error as much as possible in every trial. In addition, endpoint variance was used as an additional measure of endpoint performance to quantify the within-subject variability. The assessment of both of these endpoint performance measures is necessary because they provide different information on performance (accuracy vs variability) and can be dissociated relative to each other depending on the degree of asymmetry in the distribution of final endpoint positions relative to the target(13). It was hypothesized that tRNS applied during practice would lead to a higher rate of motor skill acquisition compared to practice alone performed during SHAM stimulation. In contrast to this original hypothesis, the findings indicated that the rate of reduction in endpoint error and endpoint variance observed in the four practice blocks was similar for the tRNS and SHAM groups. Thus, motor skill acquisition significantly improved with practice of the golf putting task, but this improvement was not different for the two stimulation conditions. These findings are contrary to the results of two previous studies that reported that tRNS enhanced performance in a serial reaction

time task (25) and in a handwriting task (15). However, the results are consistent with another study that found that tRNS failed to increase performance in a visuomotor isometric force matching task involving a whole hand grip(21). Collectively, these disparate findings suggest that caution should be applied in assuming that non-invasive brain stimulation methods such as tDCS and tRNS almost always lead to increases in performance. In fact, accumulating evidence suggest that the degree to which these methods reliably increase performance depends on the details of the motor task, the age of the subject, the level of baseline skill of the participant, the number of stimulation sessions performed, and if an individual subject is susceptible to the stimulation based on various anatomical and physiological factors (see below).

tRNS and Motor Learning

Motor skill acquisition refers to a temporary change in motor performance observed during the course of a practice session, whereas motor learning is a relatively permanent change in motor performance measured in a retention test at some time point following the cessation of a practice session. Accordingly, the present study not only quantified the motor skill acquisition in the aforementioned practice blocks but also the degree of motor learning attained by the two groups of subjects in both an immediate (5 minutes post practice) and a long-term retention test (24 hours post training). Based on previous tDCS studies that had shown that increases in motor learning followed multiple consecutive daily tDCS sessions were due to an effect on consolidation (17,18), it was predicted that the tRNS group would exhibit a greater amount of motor learning in both the immediate and long-term retention tests. Contrary to this prediction, the endpoint error and endpoint variance was similar for the two groups in both of the retention tests.

Putter Kinematics and Motor Performance

The kinematics of the putter was measured to identify changes in movement mechanics that could potentially underlie any observed differences in endpoint performance due to tRNS or motor practice. The forward swing time was not different for the two groups, did not change with practice, and remained invariant across the baseline, post, and retention tests. In contrast, there was a strong trend for the face angle of the putter to become more closed for the tRNS group as the practice and stimulation period progressed. Accordingly, there was a significant *group x block* interaction for the face angle of the putter with the difference reaching a maximum in the fourth block of practice trials. However, the post hoc test just failed statistical significance ($P = 0.053$). Nonetheless, this is an intriguing finding as it implies that the application of tRNS did elicit an impact on the mechanics of task execution, but this impact was not enough to significantly influence overall task performance. This leads to the question of how could tRNS have impacted the face angle of the putter without impacting task performance to a significant degree? The most likely explanation is that the application of tRNS to the hand area of the left motor cortex (hotspot of the FDI muscle of the right hand) lead to a change in the magnitude or direction of the grip forces of the right hand or a combination of these two factors. Several interrelated lines of indirect evidence support this assertion. First, tDCS and tRNS both increase cortical excitability and tRNS usually leads to higher increases in excitability compared with tDCS (4,9). Second, this increase in excitability has been shown to not only modulated fine motor performance but can also increase the amount of maximum force that can be produced by the muscles that are directly below the anodal electrode. Accordingly, at least three studies have shown that a single session of tDCS can increase maximal force in both stroke patients and in young adults (6,23,24). Third, Rosenkranz et al. (2000) demonstrated that an acute application of tDCS

changed thumb movement direction (19). Therefore, although the current study did not have the instrumentation to measure grip forces magnitude and direction directly, it seems reasonable based on the indirect evidence provided above, to speculate that tRNS elicited changes in grip force that lead to a more closed putter face angle. This change in putter face angle would in turn lead to a greater error in the x direction for the tRNS group. However, this greater error in the x direction likely had a negligible negative effect on the overall endpoint error as the error in the y direction represented a substantially greater contribution to the overall endpoint error compared to the x direction. Collectively, these results imply that the effects of tRNS or tDCS on motor parameters such as fine motor control, muscle force magnitude, and muscle force direction could have positive or negative effects on performance of a multi-faceted, complex motor task depending on the exact details of the task.

Possible Factors Responsible for Lack of Ability of tRNS to Improve Motor Performance

The absence of an influence on tRNS on motor skill acquisition and motor learning was an unexpected finding and conflicts with some but not all of the previous studies that have investigated the influence of tRNS on motor performance refs. Similarly, the findings are contrary to the majority of tDCS studies in young adults, which typically observe and approximately 10-15% improvement in motor performance following a single application of tDCS (11). However, there are several possible explanations for the lack of ability of tRNS to improve motor performance in the current study based on the available research involving tRNS and tDCS. First, a single session of tRNS may not be sufficient to significantly improve motor performance and multiple consecutive days of stimulation may be required. Accordingly, Reis et al (2013) found that three consecutive days of tDCS improved performance by approximately 30% compared to practice alone at the end of the three days,

whereas there were no significant differences in performance at the of day 1. Second, tRNS may not have the potential to improve motor performance to an observable degree in young adults compared to populations who have a lower initial level of skill and, therefore more room for improvement with practice and stimulation (5,6). For example, a few tDCS studies have indicated that the effectiveness of tDCS scales with age (5) and level of impairment due to motor disorders (6). Specifically, tDCS was more effective at improving performance in the oldest of old adults compared to old adults who were significantly younger. Furthermore, tDCS was more efficacious in improving motor function in severely impaired stroke patients compared to less impaired stroke patients. Third, the details of the current task may have precluded the ability of tRNS to elicit a meaningful enhancement in performance. This could be due to the fact that most tRNS and tDCS studies have utilized tasks that only involved the hand, which has a larger representation area than other muscles, more direct corticomotoneuronal projections to spinal motor neurons, and may be more susceptible to non-invasive brain stimulation. Thus, it is conceivable that it may be more difficult for tRNS to improve performance in tasks that involve multi-joint, whole body movements that involve a large number of muscles. Fourth, recent evidence from tDCS studies has demonstrated that a relatively large number of subjects may be non-responders to tDCS, which is consistent with findings from other non-invasive brains stimulation methods such as rTMS and paired-associative stimulation (26). Therefore, it is possible that the group of subjects that were randomly assigned to the tRNS group in the current study may have had a relatively large number of non-responders. Fifth, some combination of the above factors could be responsible. An alternative explanation to the above factors is that it may be that tRNS may not be as effective as previously thought in improving motor performance or simply not as effective as tDCS. Future studies will have to be conducted to tease out these various issues as the design of the current study cannot discriminate between these possible explanations.

Summary

Endpoint error and endpoint variance improved with practice, but the rate of improvement was not different between the tRNS and SHAM groups. Thus, tRNS failed to enhance motor skill acquisition in this complex motor task in young adults. Similarly, endpoint error and endpoint variance were improved immediately following practice, however, the degree of improvement was similar for the tRNS and SHAM groups. Therefore, tRNS failed to augment the immediate retention of motor skill to a greater degree than SHAM. Similarly, there was no difference in the total amount of long-term motor learning observed 24 hours following the cessation of practice between the tRNS and SHAM groups. However, it seems that tRNS did impact the mechanics of golf putting performance as there was a strong trend for the face angle of the putter to become more closed for the tRNS group, which could be due to the impact of the stimulation on either the magnitude or direction of the grip forces of the right hand or a combination of these two factors. Taken together, these results suggest that tRNS influenced the execution of this motor task, but this influence did not occur in a manner that lead to an improvement in motor skill acquisition or motor learning in the current task conditions.

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CURRICULUM VITAE

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Educational Experience

Master of Science, Kinesiology

Aug 2014 - Dec 2015

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Bachelor of Science, Physical Education

Jan 2010 – Jun 2014

Universidade de Pernambuco - Escola Superior de Educação
Física
GPA: 8.85 / 10.0

Recife, PE - Brazil

Bachelor of Social Communication, Journalism

Jan 2004 - Dec 2008

Universidade Católica de Pernambuco
Experimental Project in Journalism: Documentary (writer,
producer and director), named Marias, 30-minute film about
the feminist organizations in the city of Recife, Brazil.
GPA: 6.72 / 10.0

Recife, PE - Brazil

Scholarships/Awards

Science without Borders – PhD Scholarship

Sep 2014 – Aug 2018

LASPAU – Latin America Scholarship Program of American
Universities
Selected grantee for Brazilian Science without Borders
program PhD scholarship, administered by LASPAU.

Science Without Borders - Undergraduate one year overseas program

Aug 2012 - Jul 2013

The University of Western Australia - UWA
School of Sport Science, Exercise and Health - SSEH

Courses: English Language and Academic Communication I, Motor Development & Dysfunction, Advanced Concepts in Motor Control and Learning, Physical Development, Movement and Health, Advanced Biomechanics Methods, Advanced Exercise Physiology, Musculoskeletal Rehabilitation, Data Analysis.

Granted by the Brazilian government organ called CNPq National Counsel of Technological and Scientific Development", coverage for all universities fee, four courses per semester, transportation, health insurance, food, accommodation and faculty materials.

Professional Experience

Trainer

Aug 2013 – Present

Unic - Espaço de Metas

Recife, PE – Brazil

- Trainer in a fitness gym focused on functional training, postural correction and rehabilitation programs.
- Fitness instructor
- Running trainer

Trainer and physical tester

Feb 2012 – Jun 2012

Escola Superior de Educação Física - Ginástica Funcional

Recife, PE – Brazil

- Trainer for elderly applying functional, strength and flexibility movements and developing recreational activities;
- Physical tester to evaluate progression of the training intervention

Anatomy tutor

Jul 2011 – Jun 2012

Instituto de Ciências Biológicas - Universidade de Pernambuco

- Tutor for practice classes of anatomy for physical education students
- Exams reviser
- Exams assistant

Volunteer trainer

Mar 2010 – Apr 2011

Escola Superior de Educação Física

Recife – PE, Brazil

- Weight lifting and fitness trainer for people with diabetes type II
- Events assistant

Program secretary

July 2010 - Mar 2011

Hi Academia

Recife - PE, Brazil

- Organizer, scheduler of a patented fitness program (Face2Face)
- Secretary
- Events producer for the program graduation.

Skills

Language skills

- Portuguese: Native speaker
- English: (TOEFL IBT: 83/120)

Computer skills

- Microsoft Office: Basic
- SPSS Statistic Software: Intermediate

Publications

- **ALBUQUERQUE, L. L.** ; FISCHER, K. ; JALENE, S. ; LANDERS, M. R. ; POSTON, B. . The Influence of Cerebellar Transcranial Direct Current Stimulation on Skill Acquisition in Parkinson's Disease. American College of Sports Medicine, Southwest Chapter 2015 Annual Meeting, Costa Mesa. Oct - 2015

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Events

1. Southwest American College of Sports Medicine Annual Meeting 2015 **2010 - Present**
2. American College of Sports Medicine Conference 2015
3. Tertiary English Language Program designed for CNPQ: National Council of Scientific and Technological Development from 01/07/2013 to 02/01/2013 by the Centre for English Language Teaching at The University of Western Australia.
4. 34^o International Symposium on Sports Science 2011.
5. Updating Symposium of the Brazilian Diabetes Society 2011.

- 6.** 26° ENORFF - North/Northeast Fitness and Physiotherapy Meeting 2011.
- 7.** Individualized Training for Hypertension - Theoretical bases and practical intervention. 2011. (Short-course)
- 8.** 2° Short course in Exercise and Health. 2011.
- 9.** X Academic Week of Universidade de Pernambuco. 2010.
- 10.** XI Academic Week of Universidade de Pernambuco. 2010.
- 11.** International short-course: Supplementation for performance enhancement. 2010.
- 12.** Course on strength training periodization in gymnasiums 2010.
- 13.** XXXIV Trophy N/NE CAIXA de Athletics 2010 - Judge. 2010.
- 14.** Basic course for recreation professionals - Cia do Lazer. 2010.
- 15.** Course on Core Training - Functional Training - Ms. Maria Cláudia Vanicula. 2010.
- 16.** Functional Training Course - A practical approach - Prof. Ms. Alexandre Evangelista. 2010.