

Anodal transcranial direct current stimulation over the primary motor cortex does not enhance the learning benefits of self-controlled feedback schedules

Michael J. Carter^{1,2} · Victoria Smith¹ · Anthony N. Carlsen¹ · Diane M. Ste-Marie¹

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Abstract A distinct learning advantage has been shown when participants control their knowledge of results (KR) scheduling during practice compared to when the same KR schedule is imposed on the learner without choice (i.e., yoked schedules). Although the learning advantages of self-controlled KR schedules are well-documented, the brain regions contributing to these advantages remain unknown. Identifying key brain regions would not only advance our theoretical understanding of the mechanisms underlying self-controlled learning advantages, but would also highlight regions that could be targeted in more applied settings to boost the already beneficial effects of self-controlled KR schedules. Here, we investigated whether applying anodal transcranial direct current stimulation (tDCS) to the primary motor cortex (M1) would enhance the typically found benefits of learning a novel motor skill with a self-controlled KR schedule. Participants practiced a spatiotemporal task in one of four groups using a factorial combination of KR schedule (self-controlled vs. yoked) and tDCS (anodal vs. sham). Testing occurred on two consecutive days with spatial and temporal accuracy measured on both days and learning was assessed using 24-h retention and transfer tests without KR. All groups improved their performance in practice and a significant effect for

practicing with a self-controlled KR schedule compared to a yoked schedule was found for temporal accuracy in transfer, but a similar advantage was not evident in retention. There were no significant differences as a function of KR schedule or tDCS for spatial accuracy in retention or transfer. The lack of a significant tDCS effect suggests that M1 may not strongly contribute to self-controlled KR learning advantages; however, caution is advised with this interpretation as typical self-controlled learning benefits were not strongly replicated in the present experiment.

Introduction

Knowledge of results (KR) refers to information provided to the learner following a motor response that indicates how successful the learner's outcome was relative to the task goal (Schmidt, & Lee 2011). Although there are numerous ways to effectively schedule KR for motor skill learning (for a review see Magill, & Anderson 2013), one technique that has shown distinct learning advantages is self-controlled KR schedules (for a review see Sanli, Patterson, Bray, & Lee, 2013). With this scheduling technique, one group of participants is given choice over their KR schedule during practice (i.e., self-controlled group), while another group is matched to a self-controlled participant and replicates the respective KR schedule without any choice (i.e., yoked group). Thus, both the frequency and timing of KR provision is identical between the self-controlled and yoked groups, while only the provision or withholding of choice over feedback schedule differs. This learning advantage of self-controlled KR over yoked KR is a robust finding in the motor learning literature and it has been shown with discrete (e.g., Carter, Carlsen, & Ste-Marie, 2014), serial (e.g., Patterson, & Carter 2010),

At the time of data collection, Michael J. Carter was with the School of Human Kinetics at the University of Ottawa. He is now with the Centre for Neuroscience Studies at Queen's University.

✉ Michael J. Carter
carterjmike@gmail.com; carter.michael@queensu.ca

¹ School of Human Kinetics, University of Ottawa, Ottawa, ON, Canada

² Centre for Neuroscience Studies, Queen's University, Kingston, ON, Canada

as well as continuous (e.g., Huet, Camachon, Fernandez, Jacobs, & Montagne, 2009) motor skills.

The effectiveness of self-controlled practice conditions for motor learning are typically accounted for using a motivational influences or an information-processing explanation (for a review see Sanli et al. 2013). According to a motivational influence, when learners are given the freedom to exercise choice during practice, this choice is intrinsically rewarding, autonomy-supportive, protects perceptions of competency, and increases self-efficacy; all which enhance intrinsic motivation and motor learning (Chiviawosky 2014; Chiviawosky, Wulf, & Lewthwaite, 2012; Lewthwaite, & Wulf 2012). However, there are many findings in the extant self-controlled practice literature that are particularly difficult to reconcile from this motivational perspective (e.g., Carter et al. 2014; Carter, & Patterson 2012; Carter, & Ste-Marie 2016; Chiviawosky, Wulf, de Medeiros, Kaefer, & Wally, 2008, 2012; Chiviawosky, & Wulf 2005; Fischman 2015; Hansen, Pfeiffer, & Patterson, 2011; Patterson, Carter, & Sanli, 2011; Patterson, & Lee 2008; Sanli, & Lee 2013; Ste-Marie, Vertes, Law, & Rymal, 2013), and it has been shown that both intrinsic motivation and self-efficacy cannot account for the learning advantages of self-controlled feedback schedules compared to yoked schedules using causal modelling techniques (Ste-Marie, Carter, Law, Vertes, & Smith, 2015). In contrast, it has been proposed that the learning advantages associated with self-controlled practice conditions arise due to participants in the self-controlled group engaging in more effective and/or effortful information-processing activities during practice, which are not similarly engaged when practicing in a yoked group (Bund, & Wiemeyer 2004; Carter et al. 2014; Janelle, Kim, & Singer, 1995; Janelle, Barba, Frehlich, Tennant, & Cauraugh, 1997; Patterson et al. 2011; Patterson, & Lee 2010). Post, Fairbrother, and Barros (2011), for example, found that participants in the self-controlled group took significantly longer to initiate each trial (i.e., preparation time) than their yoked counterparts, which was interpreted as an indicator of more effortful processing activities under self-controlled relative to yoked practice conditions. This increase in response preparation time also suggests that these differences in information-processing activities between self-controlled and yoked groups can be localized to non-movement periods between trials. In KR research, three important non-movement intervals can be defined in relation to the temporal placement of the KR presentation. These are the KR-delay interval, the post-KR interval, and the intertrial interval. The KR-delay interval represents the time between the end of a motor response and the presentation of KR for that trial (Swinnen 1988), whereas the post-KR interval refers to the period between the receipt of KR and the start of the next practice trial (Magill 1988). Together, the KR-delay and the post-KR

intervals make up the intertrial interval (Schmidt, & Lee 2011). Recent self-controlled KR research has revealed that the KR-delay (Carter, & Ste-Marie 2016) and the post-KR (Grand et al. 2015) intervals are both critical time periods for the learning advantages associated with self-controlled KR schedules.

Carter and Ste-Marie (2016) demonstrated that the typical learning benefits of self-controlled KR schedules could be eliminated when the KR-delay interval was interposed with a number-solving task. As the KR-delay interval begins when a motor response ends, it is considered the period when participants engage in error detection processes (Sherwood 2010; Swinnen 1988, 1996) by comparing the actual and predicted sensory consequences of the motor response (Schmidt 1975; Wolpert, Diedrichsen, & Flanagan, 2011). Carter and Ste-Marie concluded that these error detection processes were disrupted in the self-controlled group that engaged in the secondary number-solving task, and as a result, could not be used as the basis for the KR decision. In other words, because a reliable error signal between predicted and actual sensory consequences could not be generated, these participants were unable to self-schedule their limited KR requests in a way that maximized the informational value of the KR received (see Hansen et al. 2011 for a similar discussion).

The importance of the post-KR interval for self-controlled KR learning advantages was revealed by Grand et al. (2015) who investigated feedback processing with event-related potentials (ERPs) time-locked to the receipt of KR. In particular, Grand et al. were interested in the feedback-related negativity (FRN) component of the ERPs waveform, which is a negative deflection that peaks approximately 150–300 ms after feedback presentation (Luft 2014). The results indicated that the amplitude of the FRN component was significantly larger in the self-controlled group compared to the yoked group, which suggested that the self-controlled group was engaged in increased processing of the KR during the post-KR interval. Taken together, the work of Carter and Ste-Marie (2016) and Grand et al. (2015) make it reasonable to conclude that the effectiveness of self-controlled KR schedules is dependent on the information-processing activities engaged during the KR-delay and post-KR intervals.

The importance of processing activities during the KR-delay and post-KR intervals for motor learning is further underscored with data from experiments employing disruptive transcranial magnetic stimulation (TMS) protocols (e.g., Hadipour-Niktarash, Lee, Desmond, & Shadmehr, 2007; Lin, Fisher, Winstein, Wu, & Gordon, 2008; Lin, Fisher, Wu, Ko, Lee, & Winstein, 2009; Lin, Winstein, Fisher, & Wu, 2010). For example, applying disruptive single-pulse TMS over the primary motor cortex (M1) immediately upon movement completion during the

KR-delay interval impaired retention of a visuomotor skill compared to when M1 was stimulated 700 ms after the end of a movement (Hadipour-Niktarash et al. 2007). Critically, this impaired retention (i.e., faster “washout”) was not due to differences in the acquisition of the visuomotor transformation as both TMS groups showed normal rates of adaptation. Hadipour-Niktarash et al. concluded that neural processing in M1 associated with movement error detection during the early portion of the KR-delay interval has a strong contribution to the retention of motor memories. Further support that the M1 is an important neural correlate of error-based information-processing activities during non-movement periods have been reported in a series of experiments by Lin et al. (2008, 2009, 2010). In contrast to Hadipour-Niktarash et al., Lin et al. administered disruptive single-pulse TMS during the post-KR interval and found that the retention of three different spatiotemporal arm patterns was significantly reduced. Collectively, the results of Hadipour-Niktarash et al. and Lin et al. highlight that the retention of motor memories can be attributed to error-related processing in M1 that occurs immediately after a motor response (i.e., during the KR-delay interval) and following the provision of KR for a just completed motor response (i.e., during the post-KR interval).

Although the learning advantages of self-controlled KR schedules are well-documented, an outstanding question is what brain regions contribute to these beneficial processing activities. Based on the reviewed self-controlled research identifying the KR-delay and post-KR intervals as vital periods for self-controlled KR learning benefits (Carter, & Ste-Marie 2016; Grand et al. 2015) and the data revealing that neural processing in M1 during these non-movement periods is essential for the retention of motor memories (Hadipour-Niktarash et al. 2007; Lin et al. 2008, 2009, 2010), it is reasonable to suggest that M1 may be a key neural correlate for self-controlled KR learning advantages. The purpose of the present experiment was to investigate whether combining a self-controlled KR schedule with anodal transcranial direct current stimulation (tDCS) applied over the M1 would have an additive benefit on motor learning. tDCS consists of passing a weak electrical current (e.g., 0.5–2 mA) between scalp-mounted electrodes that can influence cortical excitability in a polarity-dependent manner (see Filmer, Dux, & Mattingley, 2014; Nitsche et al. 2008 for respective reviews). Anodal stimulation has been shown to increase excitability, whereas cathodal stimulation can decrease excitability (Nitsche, & Paulus 2000, 2001). Depending on the duration of stimulation, these changes in excitability can outlast the actual stimulation period. Anodal-tDCS has been shown to enhance motor performance and learning on an isometric pinch force task (Marquez, Zhang, Swinnen, Meesen, & Wenderoth, 2013; Reis et al. 2009), during sequence learning (Cuypers et al.

2013; Katak, Mummidisetty, & Stinear, 2012), and on hand dexterity tests (Christova, Rafolt, & Gallasch, 2015; Fregni et al. 2006). Although TMS in its repetitive application (rTMS) can produce similar effects (e.g., Baraduc, Lang, Rothwell, & Wolpert, 2004; Reis et al. 2008; Richardson et al. 2006), tDCS is easier to administer and the required equipment is more portable and costs significantly less; thus, there is increased interest in the use of tDCS in clinical and rehabilitation contexts (Schulz, Gerloff, & Hummel, 2013). Additionally, the application of tDCS does not produce similar physiological artifacts as those resulting from TMS (e.g., muscle twitches, clicking noise) and tDCS can also be administered while a person is physically performing a motor task (i.e., online) without unwanted interference. This is an advantage of tDCS considering there is evidence to suggest that anodal-tDCS applied over M1 is more effective for learning when it is applied concurrently with practice (Sriraman, Oishi, & Madhavan, 2014; Stagg, Jayaram, Pastor, Kincses, Matthews, & Johansen-Berg, 2011).

Based on past tDCS research, we expected enhanced learning for the self-controlled group receiving anodal-tDCS compared to the self-controlled group receiving sham-tDCS as measured using delayed retention and transfer tests (Katak, & Winstein 2012; Schmidt, & Bjork 1992). Independent of tDCS, it was expected that both self-controlled KR groups would demonstrate greater learning than their respective yoked groups (for a review see Sanli et al. 2013).

Methods

Participants

Data were collected from 44 healthy individuals ($M_{\text{age}} = 20.73$, $SD = 1.58$; $M/F = 20/24$) with no self-reported history of cognitive or motor dysfunction and were recruited from the undergraduate and graduate student population at the University of Ottawa. All participants were right-handed as verified using the Edinburgh Handedness Inventory (Oldfield 1971) and provided written informed consent.

Task and apparatus

The task goal was to use extension-flexion movements about the elbow of the non-dominant (left) arm to replicate a criterion waveform as accurately as possible (see Fig. 1). The left arm was placed in a custom manipulum that allowed measurement of movement about the elbow in the horizontal plane. The motor task consisted of two rapid elbow extension-flexion reversal movements

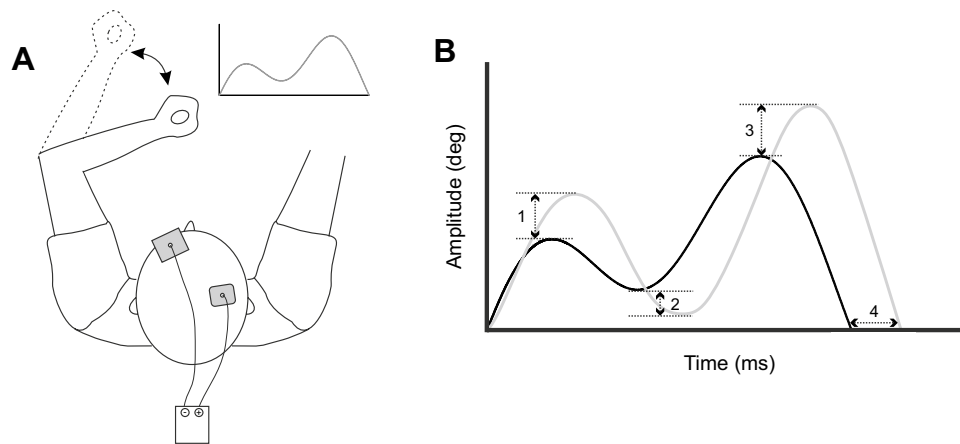


Fig. 1 **a** Top-down view of participant setup and the goal waveform that participants had to match by performing two rapid elbow extension-flexion reversals. For tDCS, the anode (*rounded electrode*) was positioned over C4, whereas the cathode (*square electrode*) was placed over the contralateral supraorbital ridge. **b** The *black line* represents the goal waveform and the *gray line* represents a participant's

waveform. Spatial accuracy was quantified by summing the absolute constant error at each reversal point which are represented by numbers 1 through 3 ($\sum |CE|_{\text{amp}}$). Temporal accuracy was quantified as the absolute constant error in movement time with respect to the goal time which is represented by number 4 ($|CE|_{\text{MT}}$)

with specific amplitude and temporal constraints, and an overall movement time goal of 900 ms (during the practice and retention phases). For the transfer test the same waveform trajectory was used, but the overall goal movement time was increased to 1150 ms. Variations of this task have been successfully used by motor learning researchers investigating the effects of non-invasive brain stimulation techniques (i.e., TMS) on motor memory encoding and consolidation processes (e.g., Kantak, Sullivan, Fisher, Knowlton, & Winstein, 2010; Lin, Fisher, Wu, Ko, Lee, & Winstein, 2009).

Participants sat in a chair facing a 22-inch computer monitor with their left forearm resting semiprone in a padded armrest attached to the top of the manipulandum. The starting position required participants to have their elbow bent at approximately 90° in front of their torso with their hand grasping a handle that could be adjusted to ensure the central axis of rotation was collinear with the elbow joint, and vision of the arm and the manipulandum were occluded. A linear potentiometer powered by a 5 V direct current power supply attached to the central axis of the manipulandum provided position data which was sampled at 1000 Hz for the duration of each movement using analog-to-digital hardware (PCIe-6321, National Instruments Inc.). A customized LabVIEW (National Instruments Inc.) program controlled the timing of all experimental stimuli on each trial, and recorded and stored the data for offline analysis.

Procedure

Upon arrival to the laboratory, participants completed a non-invasive brain stimulation screening questionnaire (Rossi et al. 2009). The first 22 participants were randomly assigned to one of the two self-controlled groups, while the last 22 participants were randomly assigned to one of the two yoked groups. This resulted in four experimental groups: self-controlled with anodal-tDCS (hereafter self-anodal), self-controlled with sham tDCS (hereafter self-sham), yoked with anodal-tDCS (hereafter yoked-anodal), and yoked with sham tDCS (hereafter yoked-sham). Sham tDCS groups were included to control for any possible effects due to the presence of the electrodes on the scalp and the initial tingling sensation that is felt during the ramping up phase at the onset of stimulation.

All participants completed 80 practice trials (8 blocks of 10 trials) of the waveform matching task on Day One. For the practice phase, the self-controlled groups were informed that they would have the opportunity to choose whether they wanted to receive KR after a trial, but with the restriction they would only have three KR opportunities per block of ten trials and that all three had to be used (Carter et al. 2014; Chiviacowsky, & Wulf 2005). Once all three requests had been used in a block, the KR decision prompt was no longer displayed after a trial. This ensured all participants practiced with a relative KR frequency of 30%; thus, any learning differences between groups could

not be attributed to receiving different amounts of KR. The yoked groups were told that KR would be provided three times in each practice block based on a predetermined schedule.

Each trial began with the goal waveform displayed for 2 s, followed by a visual “Get Ready” and then an auditory “Go” signal (1 s apart). Participants were informed that they could start their movement when ready following the “Go” signal, but that it was not a reaction time task. No visual feedback was provided during the motor responses. For the self-controlled groups, a KR decision prompt (if KR trials remained unused in a block) was displayed 3 s following the end of movement (i.e., KR-delay interval), whereas the yoked groups experienced the same 3 s interval but with a blank screen. On KR trials, KR was displayed for 3 s and consisted of a graphic representation of the participant’s displacement trace superimposed on the goal waveform. On no-KR trials, a blank screen was displayed for 3 s. Approximately 24-h after completing the practice phase, participants returned to the laboratory and performed delayed retention and transfer tests (both one block of ten trials) without KR.

tDCS protocol

tDCS (1 mA, current density = 0.128 mA/cm² at the active electrode) was administered for 18 min using a Dupel iontophoresis constant current delivery device (Empi) connected to a pair of electrodes. Stimulation was administered while participants were performing the task in the practice phase, which lasted approximately 18 min. The active electrode (sponge electrode, 1.5 ml, 7.8 cm²; Ionto+) was saline-soaked (0.9% NaCl) to create a conducting medium between the electrode and the scalp. A large reference electrode (carbon foam, 39 cm²; Ionto+) was used as the larger surface area allowed the current density to be sufficiently low such that it would have a negligible effect on underlying cortical areas (Nitsche et al. 2008). The active electrode was centered over electrode site C4 of the International 10–20 EEG system using the procedures outlined by DaSilva and et al. (2011), wherein 20% of the auricular measurement was calculated and this value (~4 cm) was then measured from Cz through the auricular line. Neuroimaging studies have shown that C3/C4 correspond to the scalp locations directly over left and right M1, respectively (Okamoto et al. 2004). This spot has been used successfully in previous experiments to elicit behavioral changes following tDCS applied to the right M1 (e.g., Cogiamanian, Marceglia, Ardolino, Barbieri, & Priori, 2007; Tecchio et al. 2010). The reference electrode was positioned over the contralateral supraorbital ridge (Reis et al. 2009; Reis, & Fritsch 2011). Both electrodes were self-adhesive, but additional foam underwrap was used to hold the electrodes

in place, thereby ensuring optimal contact throughout stimulation. For anodal-tDCS groups, the active electrode was the relative positive terminal where positive current flowed into the body and the reference electrode was the relative negative terminal where the positive current then exited the body (DaSilva et al. 2011). For the sham-tDCS groups, the stimulator was only powered on while ramping up to 1 mA (~15 s) and was then immediately shut off without the participant’s awareness. Past research has shown that participants are unable to detect a difference between real and sham stimulation with this procedure (Gandiga, Hummel, & Cohen, 2006). All participants tolerated the tDCS very well and no adverse effects were reported.

Dependent measures and statistical analyses

Given that the goal waveform had specific spatial and temporal requirements, separate measures for spatial and temporal accuracy were used. Using the procedures of Lin et al. (2009), temporal accuracy was quantified using absolute constant error (ICEI) of movement time with respect to the goal time (ICEI_{MT}; see Fig. 1) and spatial accuracy was quantified using the sum of ICEI in movement amplitude for each reversal point in the movement trajectory ($\sum \text{ICEI}_{\text{Amp}}$; see Fig. 1). For the practice phase, mean ICEI_{MT} and $\sum \text{ICEI}_{\text{Amp}}$ were analyzed using separate 2 (KR schedule: self, yoked) \times 2 (tDCS: anodal, sham) \times 8 (block) mixed-model analysis of variance (ANOVA) with repeated measures on Block. For the retention and transfer tests, mean $\sum \text{ICEI}_{\text{Amp}}$ and ICEI_{MT} were analyzed using separate 2 (KR schedule) \times 2 (tDCS) two-way ANOVAs. Differences with a probability of ≤ 0.05 were considered significant and partial eta squared (η^2_p) is reported as an estimate of effect size. Post-hoc analyses were performed using Tukey’s HSD and in cases where the assumption of sphericity was violated, Greenhouse–Geisser adjusted *P* values are reported.

Results

Spatial accuracy

Practice

$\sum \text{ICEI}_{\text{Amp}}$ decreased across practice blocks for all groups (Fig. 2), which was supported by a significant main effect for Block, $F(7, 280) = 25.58$, $P < 0.001$, $\eta^2_p = 0.39$. There was a trend for an advantage of anodal-tDCS versus sham-tDCS in the expected direction ($P = 0.08$); however, this difference did not reach conventional levels of significance. The tDCS \times Block interaction, $F(7, 280) = 4.95$, $P < 0.001$, $\eta^2_p = 0.11$, was significant and post-hoc analyses revealed for participants that received anodal-tDCS,

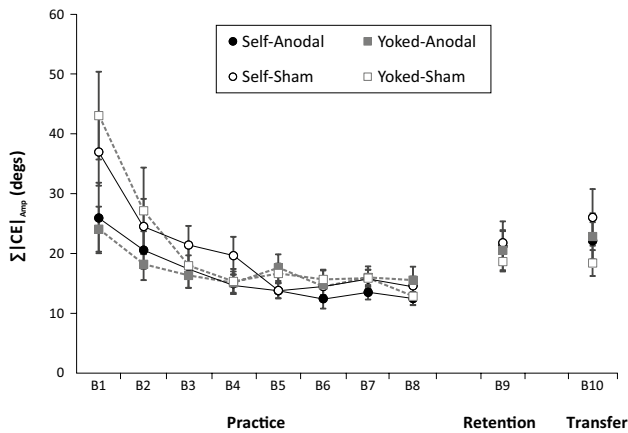


Fig. 2 Mean $\sum|CE|_{Amp}$ (\pm SE) for the practice phase (B1–B8) and the 24-h retention (B9) and transfer (B10) tests. Each block consisted of ten trials and KR was only available during Blocks 1 through 8

Block 1 was less accurate than Blocks 4, and 6–8. Similarly, the participants that received sham-tDCS were less accurate in Block 1 compared to Blocks 2–8 and Block 2 compared to Blocks 4–8. Importantly, in Block 1 participants that received sham-tDCS were not significantly less accurate than the anodal-tDCS participants. All other main effects and interactions were not statistically significant (P values >0.05).

Retention

There were no significant main effects or interactions as all comparisons for mean $\sum|CE|_{Amp}$ (Fig. 2, middle) were not statistically significant (P values >0.05).

Transfer

Similar to retention, there were no significant effects for any factors as all comparisons for transfer (Fig. 2, right) failed to reach statistical significance (P values >0.05).

Temporal accuracy

Practice

Mean $|CE|_{MT}$ decreased across practice blocks for all groups (Fig. 3, left), which was supported by a significant main effect for Block, $F(7, 280)=17.15, P<0.001, \eta^2_p = 0.30$. Post-hoc analyses revealed that timing error was significantly greater in Block 1 compared to Blocks 2–8. All other main effects and interactions were not statistically significant (P values >0.05).

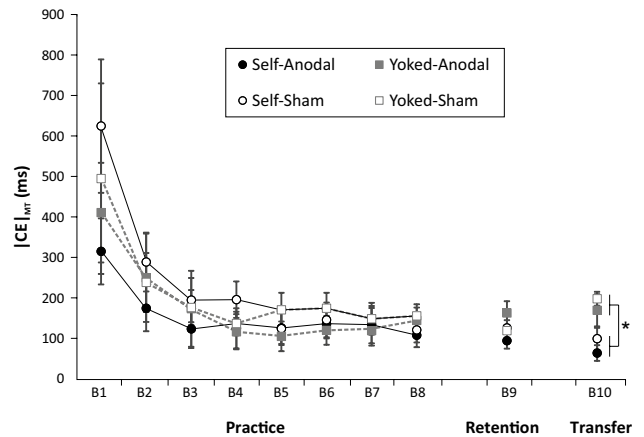


Fig. 3 Mean $|CE|_{MT}$ (\pm SE) for the practice phase (B1–B8) and the 24-h retention (B9) and transfer (B10) tests. Each block consisted of ten trials and KR was only available during Blocks 1 through 8. The asterisk (*) denotes the significant main effect for KR schedule ($P=0.001$) where a self-controlled KR schedule (i.e., self-anodal and self-sham groups) resulted in significantly less timing error during transfer than a yoked KR schedule (i.e., yoked-anodal and yoked-sham groups)

Retention

There were no significant main effects or interactions as all analyses for mean $|CE|_{MT}$ (Fig. 3, middle) were not statistically significant (P values >0.05).

Transfer

There was a significant main effect of KR schedule, $F(1, 40)=13.98, P=0.001, \eta^2_p = 0.26$, whereby the self-controlled KR groups demonstrated less timing error compared to the yoked KR groups (Fig. 3, right). All other main effects and interactions were not statistically significant (P values >0.05).

Discussion

Although the effectiveness of self-controlled KR schedules compared to yoked KR schedules is well-documented in the motor learning literature, the brain regions contributing to these learning benefits remain unclear. In the present experiment, we examined whether applying anodal-tDCS over the M1 concurrently with practice would enhance the learning benefits of self-controlled KR schedules. Contrary to this prediction, the results showed that retention and transfer performance for both the self-anodal and the self-sham groups did not differ significantly in terms of either spatial or temporal accuracy. We also anticipated that practicing with a self-controlled KR schedule, independent of

tDCS, would result in superior learning than practicing with a yoked KR schedule. This prediction was only partially supported as the self-controlled KR groups demonstrated less timing error in transfer, but not for retention, and no significant effect of KR schedule was found for spatial accuracy in either retention or transfer.

The main finding from the current experiment is that a motor skill transfer advantage was found for participants that were provided the opportunity to self-schedule their KR (i.e., self-anodal and self-sham groups) throughout the practice phase. While we had expected that self-controlled KR learning advantages would have emerged during both retention and transfer, our finding that the self-controlled KR groups were only significantly more accurate in generalizing their learning to a novel task variation than the yoked groups is not unprecedented in the self-controlled literature (e.g., Chiviawsky, & Wulf 2002; Fairbrother, Laughlin, & Nguyen, 2012; Grand et al. 2015; Hansen et al. 2011). As such, some researchers have suggested that transfer tests may be a more sensitive measure of learning than retention of a previously practiced skill (e.g., Chiviawsky, & Wulf 2002, 2005). Others, however, have suggested the transfer-specific learning advantages of self-controlled practice conditions are the result of self-evaluation processes which strengthen the ability to effectively adapt or scale performance when confronted with novel task requirements (Fairbrother et al. 2012; Grand et al. 2015). Indeed, previous research has provided evidence that suggests practicing with a self-controlled KR schedule increases one's sensitivity to detecting and correcting performance errors compared to yoked schedules (Carter et al. 2014; Carter, & Patterson 2012).

In the current study, a transfer advantage was only noted for timing accuracy and not for spatial accuracy. One possible explanation to account for this unexpected result is that the task variation that was introduced during the transfer phase was a change in the overall movement time goal (from 900 to 1150 ms), while the spatial goals were held constant. In other words, the spatial goals were identical to those experienced during practice and retention and the data revealed no groups differences at the end of practice or in retention. Based on these data, it is not entirely surprising that the transfer advantage was only seen in the temporal domain, as this was the only parameter for which participants had to scale their performance. In terms of the self-controlled literature, it remains an outstanding issue as to why self-controlled KR learning advantages only emerge in transfer in some experiments, whereas these learning benefits are apparent in both retention and transfer in other experiments.

To our knowledge, this experiment was the first to incorporate a neurostimulation technique in a self-controlled KR experiment to determine whether M1 contributes to

the well-known learning advantages of self-controlled KR schedules. We did not find a significant effect for tDCS in either retention or transfer, which suggests that M1 may not be strongly implicated in the learning benefits associated with self-controlled KR schedules. Our selection of targeting M1 was based on past research identifying M1 as an important neural correlate of the KR-delay and post-KR intervals for motor learning (Hadipour-Niktarash et al. 2007; Lin et al. 2008, 2009, 2010), and that information-processing activities engaged during these intervals are essential for gaining self-controlled KR learning benefits (Carter, & Ste-Marie 2016; Grand et al. 2015). The lack of a significant effect for tDCS is not consistent with past motor learning research where beneficial online (i.e., during practice) and/or offline (i.e., consolidation) effects of anodal-tDCS applied over M1 concurrently with motor training have been reported (e.g., Christova et al. 2015; Katak et al. 2012; Nitsche et al. 2003; Reis et al. 2009). One reason for this inconsistency in findings may relate to how motor performance and learning were quantified in the present experiment compared to previous experiments. Specifically, learning benefits of tDCS have typically been inferred based on pre- and post-tDCS differences in reaction and/or movement time (Christova et al. 2015; Katak et al. 2012). The fact that differences are found using these two measures is not surprising from a neural activation perspective (Carlsen, Maslovat, & Franks, 2012; Hanes, & Schall 1996) given that anodal-tDCS has been shown to increase cortical excitability (Nitsche, & Paulus 2001); thus, the time required to further raise activation over an initiation threshold would be reduced compared to sham-tDCS. In contrast, motor learning was evaluated in the present experiment with respect to the memorial quality of matching specific amplitude goals and an overall timing goal. As such, our findings suggest that the effectiveness of tDCS for optimizing motor learning may, in part, depend on the measures used to quantify learning.

Additionally, the current density used in the present experiment (0.128 mA/cm^2) was much higher than in most studies using a similar electrode montage ($<0.1 \text{ mA/cm}^2$), and it is therefore possible that tDCS at this high current density is less effective. Indeed, some researchers have shown a reversal of intended stimulation effects at higher densities (see Batsikadze, Moliadze, Paulus, Kuo, & Nitsche, 2013). We, however, argue against the likelihood of these possibilities based on two recent findings. First, other researchers have successfully used higher current densities ($>0.12 \text{ mA/cm}^2$) to elicit behavioral changes (e.g., Carlsen, Eagles, & MacKinnon, 2015; Carter et al. 2015, 2016; Katak et al. 2012). Second, a recent meta-analysis by Hashemirad et al. (2016) showed the biggest effect size for a single session of anodal-tDCS was in Katak et al.'s (2012) experimentation in which they also used

a small active electrode (8 cm²) and high current density (0.125 mA/cm²). Another possible factor is that with the higher current density it was possible that participants were not adequately blinded to the stimulation (O'Connell et al. 2012) and this could have contributed to the lack of a tDCS effect. This seems unlikely, however, given that we used a between-groups rather than within-subjects design (see Russo, Wallace, Fitzgerald, & Cooper, 2013; Woods et al. 2016), and thus participants only experienced tDCS a single time and were never made aware that they may or may not receive real tDCS. As such, we are confident that our lack of a tDCS effect is not attributable to either our high current density or an inadequate blinding of participants. However, some potential limitations of our tDCS protocol are that M1 excitability changes were not assessed, and thus we cannot rule out that the stimulation had a smaller than expected effect or those other brain regions were unaffected. Although our stimulation location was determined using procedures used by others (Cogiamanian et al. 2007; DaSilva et al. 2011; Tecchio et al. 2010), this location was not confirmed using TMS for example and given our small active electrode it may not have sufficiently covered the movement representation for the motor task.

A final consideration relates to the brain region that was targeted in the present experiment. Although past research has shown that M1 is involved in the formation and retention of memory representations of recently acquired motor skills (Hadipour-Niktarash et al. 2007; Lin et al. 2008, 2009, 2010; Muellbacher et al. 2002), in the context of self-controlled KR schedules, M1 may not be a primary brain region contributing to the learning advantages. From a theoretical standpoint, a better understanding of the brain regions involved in these learning advantages would prove useful in characterizing the underlying mechanisms and may also provide an avenue for unifying components of the motivational influences and information-processing perspectives (Carter et al. 2014; Wulf, & Lewthwaite 2016). While debate continues between these two perspectives (for a discussion see Sanli et al. 2013), some researchers have highlighted the importance of KR processing and error detection capabilities (Carter et al. 2014; Carter, & Ste-Marie 2016; Fairbrother et al. 2012; Grand et al. 2015). As such, it may be more appropriate for future studies to target brain areas that are more traditionally associated with the integration of sensory information for response evaluation and/or planning processes, such as the cerebellum (Crisicimagna-Hemminger, Bastian, & Shadmehr, 2010), the posterior parietal cortex (Della-Maggiore, Malfait, Ostry, & Paus, 2004), and/or the supplementary motor area (Stock, Wascher, & Beste, 2013). For instance, the cerebellum may be a good candidate reason given its theoretical role in motor learning (i.e., internal forward models) (Miall, & Wolpert 1996; Wolpert et al. 1998, 2011; Wolpert, &

Flanagan 2001) and support for this role in error-driven motor learning paradigms (Bastian 2008; Criscimagna-Hemminger et al. 2010; McDougale, Ivry, & Taylor, 2016).

In conclusion, a significant role for M1 in the learning benefits of self-controlled KR schedules was not found in the present experiment using anodal-tDCS. Although continued investigation into uncovering the brain regions is highly encouraged in the self-controlled motor learning literature, it may be more fruitful for these future studies to use more focal forms of non-invasive brain stimulation, such as disruptive TMS protocols (e.g., Hadipour-Niktarash et al. 2007) or HD-tDCS (e.g., Kuo et al. 2013). A better understanding of the relevant brain structures and their associated functions would prove valuable for our understanding of why self-controlled KR schedules enhance learning at a theoretical level.

Compliance with ethical standards

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Conflict of interest None.

Ethical standards All participants gave written informed consent prior to inclusion in the studies and the studies were conducted in accordance with the ethical guidelines of the University, and hence with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments.

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