DISABILITY AND REHABILITATION
https://doi.org/10.1080/09638288.2020.1827303

Taylor & Francis
Taylor & Francis Group

ORIGINAL ARTICLE



# Effects of cerebellar transcranial direct current stimulation (tDCS) on motor skill learning in swallowing

Kerstin L. C. Erfmann[a,b], Phoebe R. Macrae[a,b], Richard D. Jones[c,d,e], Esther Guiu Hernandez[a,b] and Maggie-Lee Huckabee[a,b]

[a]Rose Centre for Stroke Recovery and Research, The University of Canterbury, Christchurch, New Zealand; [b]School of Psychology, Speech & Hearing, University of Canterbury, Christchurch, New Zealand; [c]Department of Electrical & Computer Engineering, Christchurch, New Zealand; [d]New Zealand Brain Research Institute, Christchurch, New Zealand; [e]Department of Medical Physics & Bioengineering, Christchurch Hospital, Christchurch, New Zealand

**ABSTRACT**

**Objective:** This study evaluated the effects of cerebellar tDCS on motor learning for swallowing.

**Methods:** In a double-blind RCT, 39 healthy adults received either sham, anodal tDCS, or cathodal tDCS in two sessions on two consecutive days. Following 20 min cerebellar tDCS (2 mA) or sham, they underwent swallowing skill training that targeted control of timing and magnitude of submental muscle activation during swallowing. Linear mixed models were used to identify the effects of stimulation on timing and magnitude accuracy as measured by the change in task performance for each training session, and for skill retention on days 3 and 10 post-intervention.

**Results:** Only the sham group had a reduced temporal error from baseline to all following timepoints. When compared to error changes in the sham group, changes from baseline in temporal errors were higher at all timepoints post-intervention for the anodal group, and higher at both retention assessments for the cathodal group. Amplitude errors were smaller for all conditions at all timepoints post-intervention compared to baseline.

**Conclusions:** Cerebellar tDCS was found to inhibit temporal aspects of motor skill learning in swallowing. For the tDCS parameters used in this study, there is no support for use of tDCS to facilitate swallowing rehabilitation.

**Trial Registry Number (https://www.anzctr.org.au/):** ACTRN12615000451505.

**ARTICLE HISTORY**
Received 15 April 2020
Revised 18 September 2020
Accepted 19 September 2020

**KEYWORDS**
Cerebellum; transcranial direct current stimulation; motor skill learning; swallowing

**➤ IMPLICATIONS FOR REHABILITATION**

- Cerebellar tDCS, in combination with motor skill training, has been demonstrated to increase motor skill learning in healthy individuals and neurologically impaired patients.
- In this study, cerebellar tDCS applied prior to swallowing skill training adversely affected timing measures of submental muscle activation during swallowing.
- In contrast to published outcomes in the corticospinal literature, both anodal and cathodal tDCS resulted in a relative inhibitory effect on motor skill learning in swallowing when compared to the sham condition.
- Swallowing skill training without tDCS produced increased accuracy in outcomes.

## Introduction

The cerebellum contributes substantially to human motor control, error correction of movements, and motor skill learning [1]. It has thus become a target for non-invasive neuromodulation techniques, such as transcranial direct current stimulation (tDCS), with the aim to improve motor skill learning by modulating cerebellar function in healthy individuals and in individuals with neurological disorders.

TDCS uses anodal (positively charged) and cathodal (negatively charged) electrodes to either depolarize or hyperpolarize neural tissue underneath the electrodes through current flow [2,3]. TDCS applied over the cerebellum has been demonstrated to evoke neurophysiological and behavioral changes in motor function in healthy volunteers [4–6]. Galea and colleagues [4] evaluated of 2 mA tDCS over the right cerebellar hemisphere for 25 min using a paired-pulse transcranial magnetic stimulation (TMS) paradigm. They measured changes in cerebellar brain inhibition (CBI), a measure that is commonly used to assess the effects of cerebellar tDCS on corticospinal excitability. They reported that anodal tDCS when applied over the cerebellum decreased CBI whereas cathodal tDCS increased CBI. These results suggest polarity dependent effects of cerebellar tDCS.

Small direct currents of 1–2 mA for a duration of ~20 min applied over the cerebellum can effectively modulate motor behavior, as revealed in a meta-analysis by Oldrati and Schutter [7]. In contrast to the polarity-dependent neurophysiological changes of cerebellar tDCS, the direction of the behavioral

CONTACT Kerstin L. C. Erfmann kerstinerfmann@gmail.com Rose Centre for Stroke Recovery and Research at St George's Medical Centre, The University of Canterbury, Private Bag 4737, Christchurch 8140, New Zealand

changes in healthy volunteers is not consistently predictive [7]. Testing both anodal and cathodal tDCS is therefore recommended to gain further insights into neurophysiological and behavioral changes.

Clinical application of cerebellar tDCS has been investigated in many patient groups, including stroke [8]. The clinical application of tDCS for rehabilitation of motor impairments following stroke has primarily been explored for limb function using tDCS over M1 and identified additional gains in motor function using tDCS when provided in conjunction with rehabilitation [9,10]. However, there are several advantages to application of cerebellar tDCS in the event of a cerebral stroke as discussed in the review by Wessel and Hummel [11]. In addition to targeting neural structures involved in motor skill learning, treatment effects would not be influenced by lesion site or lesion size of the cerebral cortex, therefore, eliminating the question about the best stimulation site for tDCS [11]. Furthermore, placing the electrode centrally on the cerebellum leads to greater gains in motor performance in bilateral postural control tasks [12] compared to ipsilateral electrode placement when training limbs in unilateral tasks [13].

Patterned motor responses such as swallowing are commonly impaired following stroke. Swallowing disorders occur with an incidence of up to 80% in acute stroke patients [14]. Rehabilitation of swallowing, using biofeedback and skill-based training approaches have successfully been used in patients with neurological impairments [15–17]. This raises the question: would cerebellar tDCS enhance the effects of swallowing skill training? This research investigated immediate and long-term polarity-dependent effects of cerebellar tDCS on motor skill learning in swallowing in healthy volunteers. It was hypothesized that anodal cerebellar tDCS applied prior to swallowing-skill training would enhance immediate motor skill learning and long-term effects for up to one week post training. Conversely, it was hypothesized that cathodal cerebellar tDCS would inhibit motor skill learning in swallowing.

## Materials and methods

Ethical approval was obtained for this study from the regional Health and Disability Ethics Committee (15/STH/46). Informed consent was obtained from all individuals included in the study.

### *Subjects*

Healthy individuals aged 50 years and older were recruited for this study. Further inclusion criteria were normal or corrected-to-normal vision and no history of swallowing, neurological, or muscular impairment. All subjects were screened using a questionnaire to enroll participants that were safe to receive tDCS, consistent with published guidelines for participant enrolment into tDCS studies [18,19]. Approximate gender and age matching was achieved when assigning male and female participants into three age-based subgroups (50–64 years, 65–79 years, and 80+ years) within each condition (anodal tDCS, cathodal tDCS or sham).

### *Cerebellar tDCS*

Direct current was delivered using a research-version tDCS stimulator (TCT Research Ltd, Hong Kong), which includes a sham option and a password-protected stimulation setting for operator blinding. The direct current was applied *via* three rectangular rubber electrodes that exactly fitted into 5 cm × 5 cm sponge covers (soaked in 0.9% sodium chloride solution). The electrode for cerebellar stimulation was centered in the midline 1 cm below the inion. As the muscles involved in swallowing are bilaterally recruited, the two electrodes of opposite polarity were split, with one over each buccinator muscle, providing equal and bilateral stimulation. The current was ramped over 30 s and delivered at 2 mA for 20 min (current density of 0.08 mA/cm$^2$) preceding execution of the skill training task. Stimulation could not be provided concurrently with the treatment due to impact of the stimulation on the surface electromyographic (sEMG) signal. This method, applying stimulation at rest prior to the training, has been found to be as effective as stimulation applied during task training when targeting motor learning using cerebellar tDCS [13]. No current was delivered *via* the sham setting. All of the participants were naïve to tDCS and were instructed that they may receive a low current and that they may or may not feel anything.

### *Swallowing skill training*

Midline submental muscle activity (anterior belly of digastric, mylohyoid and geniohyoid) for swallowing skill assessment and training was recorded using triode-patch electrodes (Triode™ T3402M, Thought Technology Ltd, Montreal) with an inter-electrode distance of 2 cm. Data were recorded with the NeuroTrac® Simplex device portable EMG biofeedback device (Verity Ltd, UK) with a single channel displaying the root-mean-square envelope of the sEMG signal, with a sensitivity of ± 0.2 μV, sampled at 18 Hz. The Biofeedback in Strength and Skill Training software (BiSSkiT$^{CE}$), Version 1.0.0.1, displayed the acquired information as a time by amplitude waveform, in real-time on a computer screen. The x-axis represented time with a pre-set duration of each screen of 30 s. The y-axis represented the magnitude of submental muscle activity in μV, with the maximum value on the y-axis computed for each participant as 100% of the participant's calibration value, defined as the average peak amplitude of five effortful swallows.

In the skill training protocol, the BiSSkiT$^{CE}$ software randomly positioned a square target for each trial on the computer screen, varying in both the vertical and horizontal position. The participants were instructed to swallow such that the peak of the waveform (reflecting submental muscle activity) was placed inside the target, as close as possible to the centre of the box. The range of movement of the target was limited to 4–26 s on the x-axis. On the y-axis, the target movement range was limited to be between 20 and 70% of the calibration value [15,20]. The initial size of the target was set to 50% of the allowable y-axis target movement range.

The target size automatically decreased or increased by 10% following three successful or unsuccessful trials, respectively [15]. Visual on-screen feedback was provided for each successful "hit" or unsuccessful "miss," with a numerical value indicating the distance in mm from the peak of the sEMG waveform to the center of the target. Participants performed 20 min of swallowing skill training, which equated to 40 swallowing trials per training session.

### *Swallowing skill assessment*

The skill training protocol of the BiSSkiT$^{CE}$ software was used to test motor skill learning. Since the assessment of motor skill learning requires a variation of the practiced skill [21] and can only be assessed in the absence of the feedback by which the skill was obtained [22], no visual feedback was provided during these

swallowing trials. The waveform disappeared randomly 2–5 s prior to the target, requiring participants to perform the task based on their intrinsic representation of the screen and motor control model. Furthermore, since swallowing is presumably already functioning at its maximum in healthy individuals, a smaller target size of 30% (instead of the usually pre-set target size of 50%) of the allowed y-axis target movement range was chosen to provide significant challenge for the assessment. In line with the skill training protocol, the target was randomly positioned within the same time and amplitude constraints and the goal of the task remained the same. The researcher monitored the patient during this assessment and marked each swallow to ensured that the EMG peak representing each swallow could be identified in later analysis. The swallowing skill assessment consisted of 10 saliva swallowing trials at each assessment timepoint.

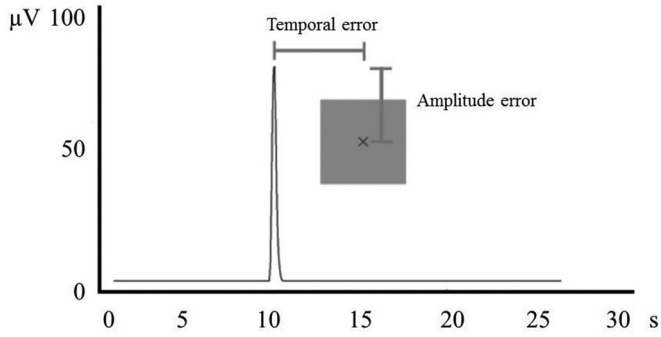


**Figure 1.** Computation of the temporal and amplitude error. Amplitude in microvolts (μV) and time in seconds (s).

### *Experimental procedures*

For this double-blind randomised controlled trial (RCT), participants were randomly assigned to one of three conditions: anodal, cathodal, and sham. A research colleague randomly assigned the participants to one of the three groups, knowing only age and gender to ensure balance between groups. All participants completed the same study protocol and completed a single training session on each of two consecutive days consisting of cerebellar tDCS preceding sEMG biofeedback swallowing skill training. Swallowing skill assessments were performed before and after these sessions, and in two follow-up sessions, on Days 3 and 10. At the end of Days 1 and 2, a comfort-rating questionnaire regarding tolerance and side effects of the tDCS intervention [23] as completed by the participant.

### *Data collection and post-processing*

The BiSSkiT$^{CE}$ software automatically selected the highest peak of the sEMG signal as the swallowing event. If the maximum value did not correspond with the observed or reported swallowing attempt (e.g., artefact due to movement), the researcher manually selected the sEMG peak associated with swallowing for the analysis.

A trial was discarded from the overall analysis if the peak was outside the range of the screen. These events may be explained by unstable electrode to skin contact, extraneous and simultaneous body movements of the participant during the swallowing attempt or accidental contact between the connection cable and the sEMG device. The researcher immediately responded following invalid trials, ensuring sufficient electrode to skin contact and by reminding the participant to inhibit extraneous movement while swallowing.

### *Statistical analysis*

The differences between the peak of the sEMG waveform and the center of the target for temporal (s) and amplitude (μV) domains were calculated, as depicted in Figure 1. These absolute error measurements were then normalized to the maximum value of each axis (relative error). The relative error was chosen to account for the differences in amplitude between and within participants across sessions, as the amplitude scale was recalibrated for each session. The relative error measurements were exported to excel and averaged across the 10 swallowing trials of each assessment. Linear mixed effects model analysis was performed in RStudio (version 3.2.5) using the packages lme4 and lmerTest [24].

### *Effects of cerebellar tDCS on motor skill learning in swallowing*

Changes in motor skill learning between and within stimulation groups across timepoints were evaluated in separate models for each of the temporal and amplitude error. In the linear mixed-effects analysis, main effects of stimulation condition and timepoint, and the interaction effect between stimulation and timepoint, were entered into the model as fixed effects, intercept for subject was included as a random effect. The inclusion of each of the fixed effects in the model was evaluated by model comparison using a likelihood ratio test. The overall effect was considered not significant and dropped from the model if the *p*-value was bigger than 0.05. Model comparisons were performed using a likelihood ratio test. The chi-square, degrees of freedom and *p*-values of this test are reported. If the likelihood ratio test was significant for any of the effects of interest, the minimal adequate model obtained from these comparisons was then evaluated, the coefficient estimates, standard error (SE), and *p*-values of this model are reported. A *p*-value of $< 0.05$ was considered significant. The stimulation condition "Sham" and the timepoint "Baseline" were set *a priori* as reference categories. This allowed evaluation of differences from baseline in motor skill learning of the stimulation conditions compared to the sham condition over time.

### *Online, offline and consolidation effects*

The impact of cerebellar tDCS on online, offline and consolidation stages of motor skill learning was tested in a separate mixed effects analysis for the two response variables (temporal and amplitude error). The learning phase (online, offline, consolidation) and stimulation condition (anodal, cathodal, sham) were included in the model as fixed effects and intercept for subject as the random effect. Model comparisons were carried out as described previously. Online effects were defined as the changes from before to after the training sessions, offline effects as the changes between consecutive sessions and consolidation effects as changes over the follow-up period where no stimulation or training took place. Calculation of the effects were performed as follows (adapted from Cantarero et al. [6]):

- Online effects = (RV Post-Day 1 – RV Baseline) + (RV Post-Day 2 – RV Pre-Day 2).
- Offline effects = (RV Pre-Day 2 – RV Post-Day 1) + (RV Follow-up 1 day – RV Post-Day 2).
- Consolidation effects = (RV Follow-up 1 day – RV Follow-up 1 week).

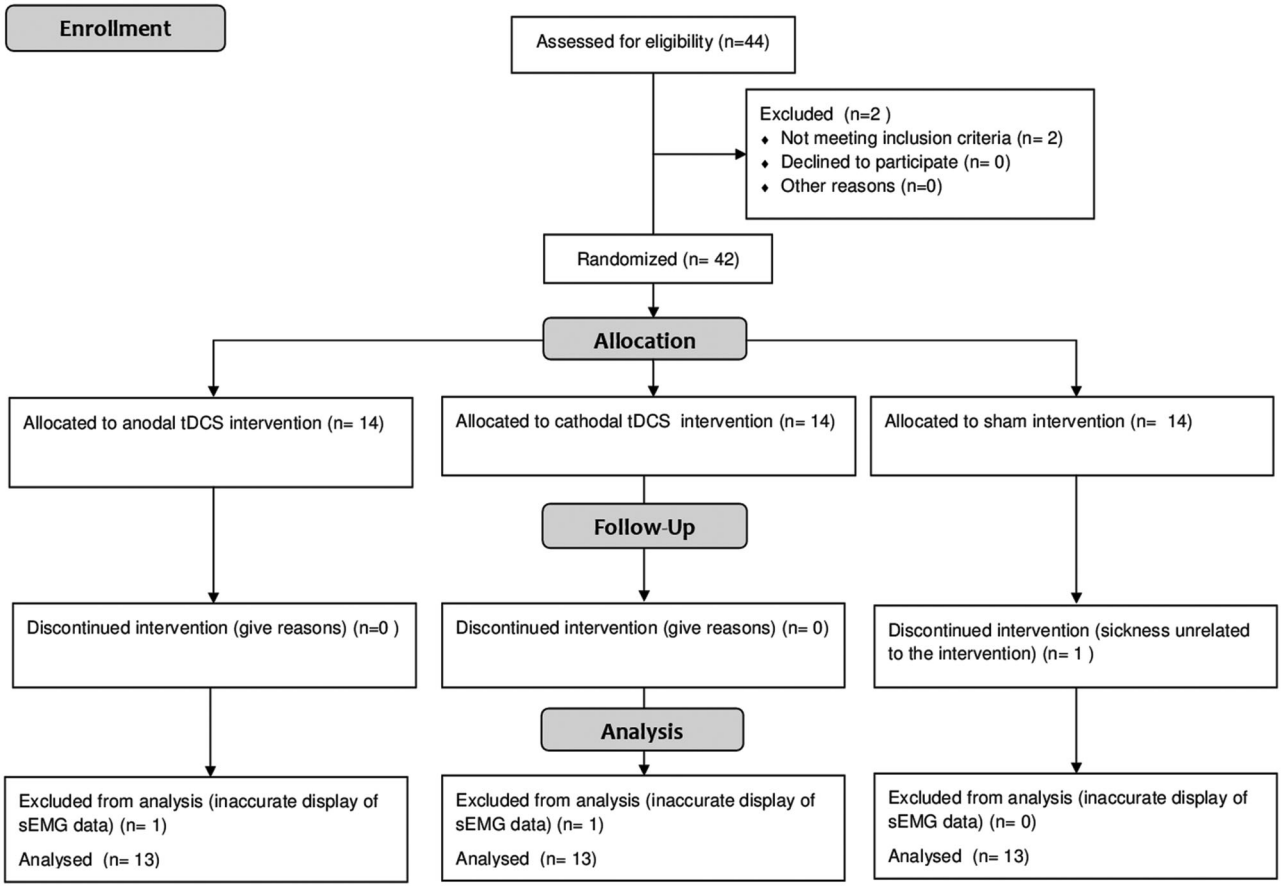


Figure 2. CONSORT flowchart (tDCS = transcranial direct current stimulation, sEMG = surface electromyography).

## Results

### *Participant characteristics*

Forty-four healthy individuals consented to participate in this study. Thirty-nine complete sets of data were collected (6 male and 7 female for each condition, Figure 2). The mean years of age of the participants in each condition was 71, ranging from 56 to 86. Data from two participants were discarded for methodological complications, including insufficient electrode-to-skin contact which resulted in an inaccurate display of the sEMG signal during data collection. Two participants were not able to follow task instructions and one withdrew because of illness unrelated to the research.

### *Data analysis*

Unusable data from 0.6% of the swallowing trials were discarded post data collection but prior to the analyses due to movement artefact in the sEMG signal. Descriptives for the amplitude and time errors at each time point for each stimulation group are reported in Table 1 as median and interquartile range (IQR). Log-transformations (natural logarithm with base e) were applied to both outcome measures (amplitude and temporal errors) in the models for the analysis of the effects of cerebellar tDCS on motor skill learning in swallowing to account for a violation of the non-constant residual variance assumption. The model coefficients were exponentiated to transform them back to their original scale. Model results are expressed in terms of geometric means and percent change between the different timepoints and stimulation groups when compared to the reference category. The assumptions were met for all other analyses.

Table 1. Median and Interquartile Range (IQR) for the time and amplitude errors across timepoints and stimulation condition.

| Stimulation condition | Timepoint | Time error (%) median (IQR) | Amplitude error (%) median (IQR) |
|---|---|---|---|
| Anodal | Baseline | 2.38 (2.17) | 14.8 (15.6) |
| | Post 1 | 2.01 (1.84) | 14.94 (7.59) |
| | Pre 2 | 2.4 (2.93) | 16.11 (8.95) |
| | Post 2 | 2.32 (2.8) | 15.61 (8.7) |
| | Follow-up Day 3 | 3.25 (3.48) | 13.37 (7.75) |
| | Follow-up Day 10 | 2.06 (2.68) | 14.93 (6.7) |
| Cathodal | Baseline | 2.77 (3.54) | 19.48 (8.52) |
| | Post 1 | 2.93 (2.43) | 16.8 (13.64) |
| | Pre 2 | 2.42 (3.08) | 17.18 (10.25) |
| | Post 2 | 2.13 (2.23) | 14.93 (6.27) |
| | Follow-up Day 3 | 2.65 (4.79) | 16.28 (11.83) |
| | Follow-up Day 10 | 2.77 (4.25) | 16.41 (12.73) |
| Sham | Baseline | 5.23 (4.91) | 23.09 (23.89) |
| | Post 1 | 3.68 (3.87) | 13.58 (15.23) |
| | Pre 2 | 2.92 (3.45) | 15.26 (15.74) |
| | Post 2 | 2.55 (2.72) | 13.93 (19.44) |
| | Follow-up Day 3 | 2.20 (3.10) | 10.73 (14.87) |
| | Follow-up Day 10 | 2.88 (3.10) | 16.20 (18.73) |

Post 1 = Post-training session 1 assessment; Pre 2 = Pre-training session 2 assessment; Post 2 = Post-training session 2 assessment.

### *Effects of cerebellar tDCS on motor skill learning in swallowing*

#### *Amplitude error*

The minimal adequate model for the amplitude error included only timepoint as a fixed effect. The likelihood ratio test was non

**Table 2.** Percentage of changes from baseline for the *amplitude error* for each timepoint regardless of stimulation conditions.

| Timepoint | % change from baseline | Lower 95% CI | Upper 95% CI | *p*-value |
|---|---|---|---|---|
| Post 1 | −22.87 | −33.44 | −10.48 | <0.001* |
| Pre 2 | −19.31 | −30.48 | −6.34 | <0.005* |
| Post 2 | −23.61 | −34.19 | −11.34 | <0.001* |
| Follow-up Day 3 | −28.88 | −37.86 | −16.29 | <0.001* |
| Follow-up Day 10 | −16.45 | −28.02 | −3.03 | =0.019* |

Post 1 = Post-training session 1 assessment; Pre 2 = Pre-training session 2 assessment; Post 2 = Post-training session 2 assessment; 95% CI = 95% confidence interval; * = statistically significant effect. Raw data was used for the statistical analysis, change from baseline is used for demonstration purposes only.

**Table 3.** Percentage of changes in the *temporal error* from baseline to each of the following timepoints for the two stimulation groups compared to the change from baseline to every other timepoint of the sham group.

| Stimulation condition and timepoint | Difference in % change from baseline when compared to % change of sham group | Lower 95% CI | Upper 95 % CI | *p*-value |
|---|---|---|---|---|
| Anodal Post 1 | 10.90 | −16.76 | 47.76 | 0.045* |
| Anodal Pre 2 | 3.84 | −22.06 | 38.35 | 0.019* |
| Anodal Post 2 | −10.68 | −32.96 | 19.01 | 0.042* |
| Anodal Follow-up Day 3 | 5.28 | −20.98 | 40.27 | <0.001* |
| Anodal Follow-up Day 10 | −13.52 | −35.09 | 15.23 | 0.025* |
| Cathodal Post 1 | −15.13 | −36.3 | 13.08 | 0.470 |
| Cathodal Pre 2 | −13.97 | −35.43 | 14.62 | 0.144 |
| Cathodal Post 2 | −22.59 | −41.9 | 3.14 | 0.175 |
| Cathodal Follow-up Day 3 | −22.14 | −41.56 | 3.74 | 0.021* |
| Cathodal Follow-up Day 10 | −4.48 | −28.31 | 27.27 | 0.007* |

Post 1 = Post-training session 1 assessment; Pre 2 = Pre-training session 2 assessment; Post 2 = Post-training session 2 assessment; 95% CI = 95% confidence interval; * = statistically significant effect. Raw data was used for the statistical analysis, change from baseline is used for demonstration purposes only.

significant for the interaction effect between stimulation and timepoint [$\chi^2(10) = 9.40$, $p = 0.50$] nor for the stimulation group [$\chi^2(2) = 1.56$, $p = 0.46$]. The likelihood ratio test was significant for timepoint [$\chi^2(5) = 21.705$, $p < 0.001$]. When evaluating the final model, a lower amplitude error at all timepoints when compared to baseline was found, with the highest estimated change recorded at follow-up Day 3, see Table 2.

#### *Temporal error*

The minimal adequate model for the time error included the interaction effect between stimulation group and timepoint with a significant likelihood ratio [$\chi^2(10) = 20.85$, $p = 0.02$]. When evaluating the final model, the three stimulation conditions were not significantly different from each other at baseline [$p > 0.30$]. The change from baseline in the anodal group was lower to the change from baseline in the sham condition at all timepoints, see Table 3. The change from baseline in the cathodal group was only lower than the change from baseline in the sham at the follow-up assessments. Only the sham group significantly decreased in the temporal target error from baseline to all other timepoints, see Table 4.

### *Online, offline and retention effects*

#### *Amplitude error*

The likelihood ratio test was not significant for the interaction effect between stimulation and timepoint [$\chi^2(4) = 4.07$, $p = 0.40$] nor for the stimulation group [$\chi^2(2) = 0.37$, $p = 0.83$]. The minimal adequate model for the amplitude error included only learning phase as a fixed effect [$\chi^2(2) = 15.83$, $p < 0.001$]. The estimated average value for the online effects was −6.024% [95% CI = −8.880, −3.168; $p < 0.001$]. The amplitude error was higher for the offline and retention effects with an estimated difference of 6.31% [95% CI = 2.277, 10.356; $p < 0.001$] for offline to online effects and 7.95% [95% CI = 3.917, 11.996; $p < 0.003$] for retention to online effects.

**Table 4.** Percentage of changes from baseline in the *temporal error* for the sham group when compared to its baseline.

| Timepoint | % change from baseline | Lower 95% CI | Upper 95% CI | *p*-value |
|---|---|---|---|---|
| Sham Post 1 | −26.93 | −44.61 | −3.59 | 0.034* |
| Sham Pre 2 | −36.50 | −51.87 | −16.23 | 0.002* |
| Sham Post 2 | −41.58 | −55.71 | −22.93 | <0.001* |
| Sham Follow-up Day 3 | −51.88 | −63.54 | −36.52 | <0.001* |
| Sham Follow-up Day 10 | −45.81 | −58.93 | −28.50 | <0.001* |

Post 1 = Post-training session 1 assessment; Pre 2 = Pre-training session 2 assessment; Post 2 = Post-training session 2 assessment; 95% CI = 95% confidence interval; * = statistically significant effect. Raw data was used for the statistical analysis, change from baseline is used for demonstration purposes only.

#### *Temporal error*

The likelihood ratio test was not significant for the interaction effect between stimulation and timepoint [$\chi^2(4) = 8.49$, $p = 0.08$] nor for the stimulation group [$\chi^2(2) = 3.08$, $p = 0.22$] nor for the learning phase [$\chi^2(2) = 5.05$, $p = 0.08$].

## Discussion

This is the first study to assess the effects of cerebellar tDCS on motor skill learning in swallowing. Both anodal and cathodal tDCS had a relative inhibitory effect on skill learning in swallowing compared to the sham condition. Cerebellar tDCS applied prior to swallowing skill training affected temporal accuracy but not the magnitude accuracy of submental muscle activation during swallowing. However, in contrast to the hypotheses and the corticospinal literature, anodal tDCS inhibited motor skill learning in the temporal aspects of swallowing. Similar to the corticospinal literature, cathodal tDCS inhibited motor skill learning of temporal accuracy when compared to the sham condition.

### *Polarity independent result*

Findings from this research contradict the majority of neurophysiological and behavioral studies on cerebellar tDCS, which have documented opposing effects for the two polarity protocols [4,25–28]. However, in line with the current study, Ferrucci and colleagues [29] found an inhibitory effect of both anodal and cathodal cerebellar tDCS at midline on reaction time in a working memory task. In contrast, Shah et al. [30] demonstrated enhanced behavioral effects for both anodal and cathodal cerebellar tDCS on motor performance of a lower-limb tracking task. The contradictory effects of the two polarities may be explained by the different tasks used to document outcomes or the different electrode placements over the cerebellum used for these investigations. For example, Ferrucci et al. [29] and the current study used an electrode placement at midline that targeted both cerebellar hemispheres simultaneously, whereas Shah and colleagues [30] utilized a unilateral electrode placement. Since the electrode placement influences the direction of the current flow through

neural tissue [31], this is could explain the opposing polarity dependent results.

### *Inhibitory effects of anodal tDCS*

In this study, anodal tDCS study resulted in a relative inhibition of temporal motor skill learning, a finding which is contrary to most commonly reported results in the corticospinal system [32]. One explanation might be found in differences in the corticobulbar and corticospinal pathways. This is supported by reports of inhibited behavioral effects following anodal cerebellar tDCS in the corticobulbar system [33], in contrast to enhanced effects of anodal tDCS reported for the corticospinal system [5]. Jayasekeran et al. [34] provided further neurophysiological evidence in support of this explanation. They demonstrated facilitory neural connections of the cerebellum for motor cortical output from the pharyngeal area using paired-pulse TMS to test CBI. This is contrary to the corticospinal system where inhibitory connections have been demonstrated using a similar neurophysiological assessment [35]. Stimulation parameters that have successfully been used to enhance motor skill learning in the corticospinal system might therefore not be transferable to corticobulbar motor tasks.

The inhibitory effects of anodal cerebellar tDCS could also be a consequence of different tDCS parameters in the current study, such as stimulation intensity or electrode placement. Computer modelling studies of cerebellar tDCS and animal studies suggest that an intensity of 2 mA is required to reach the neurons within the cerebellum [36,37]. Midline placement over the cerebellum is strong enough to evoke changes in cerebellar excitability without spreading to brainstem structures [38], causing behavioral changes, such as slower reaction times on a working memory task [29]. Therefore, a stimulation intensity of 2 mA over the cerebellum at midline was used in this study. However, dividing the reference electrode to the buccinator muscles to suit a bilaterally innervated motor task might have diminished the electric current in both of the cerebellar hemispheres to approximately 1 mA. In contrast to studies that used 2 mA over one cerebellar hemisphere, studies that used 1 mA or 1.5 mA of unilateral cerebellar tDCS reported significant but heterogeneous behavioral effects [30,39,40]. Furthermore, decreasing the tDCS intensity to 1 mA per hemisphere might have shifted the direction of excitability changes. Similar effects have been demonstrated for cathodal tDCS of M1, where inhibition changed into excitation by increasing the stimulation intensity from 1 mA to 2 mA [41]. More research is required to identify effects of different tDCS intensities and electrode placements on the same behavioral or neurophysiological outcome measures for cerebellar tDCS.

The polarity of cerebellar tDCS did not result in the polarity dependent change in behavior as hypothesized in the present study, which is in line with the results from the meta-analyses by Oldrati and Schutter [7]. The hypotheses for this study were based on the polarity dependent behavioral and neurophysiological findings from Galea and colleagues [4,5]. This research group replicated their study more recently and did not identify polarity dependent effects of cerebellar tDCS on visuomotor adaptation using the same behavioral measure [42]. The main reason for this finding is discussed as a large variability across participants to detect a measurable effect of cerebellar tDCS in a small sample of 10–15 participants. With a sample size of 13 participants per condition, variability across participants may have also affected the results of this study.

### *Cerebellar tDCS affects temporal not magnitude accuracy*

Cerebellar tDCS influenced the learning of the temporal control of submental muscle contraction but not the magnitude of muscle activation during swallowing. These findings are in line with findings from Cantarero et al. [6], who found that cerebellar tDCS only affected one component of motor learning. In their study on motor learning in the upper limb, only accuracy but not speed in a speed-accuracy trade off task was affected by cerebellar tDCS. Cantarero et al. discussed that "different components of motor skill learning (i.e., error and speed) may be predominantly controlled by different neural circuits with the cerebellum largely influencing error reduction" [6, p. 3289]. In contrast to volitional cortical control of accuracy and speed in upper limb movements, temporal and magnitude control of submental muscle activity during swallowing are components of a primarily brainstem driven, semi-reflexive motor function. However, oral and pharyngeal motor sequences during swallowing can be modulated from higher cortical centres [17,43–45]. Therefore, the results of the current study support Cantarero et al.'s [6] findings, indicating that different neural control mechanisms may be used for different components of motor skill learning, and that they may respond differently to tDCS.

### *Cathodal tDCS only inhibited long-term retention of motor skill learning*

While anodal cerebellar tDCS inhibited temporal motor learning across all timepoints, the effects of cathodal tDCS developed over time and only inhibited temporal motor learning following consolidation periods and two days of skill training. Retention of learned motor skills has been recognized to be the result of more permanent alterations in cerebellar connections in the form of long-term depression (LTD) of Purkinje cells [46]. The current study demonstrated that both polarities of cerebellar tDCS in combination with motor training might evoke LTD-like processes in the cerebellum for motor skill learning of corticobulbar motor functions.

### *Cerebellar tDCS did not differentially affect different phases of motor learning*

There were no differences between the three groups for the online learning phases (pre- to post-session) of the two days of motor skill training, nor the offline learning phases between the training and follow-up sessions. The absence of a difference between groups for online learning is contrary to findings of a similar single-case study by Cantarero and colleagues [6] in the corticospinal system. This could be the result of differences in the study protocols.

One main difference in the study protocol of this study compared to Cantarero et al. [6] was the timing of the stimulation. In the current study, cerebellar tDCS was applied prior to swallowing skill training for the following reasons. Several minutes of cerebellar tDCS have been demonstrated to result in lasting changes of neural excitability of up to 30 min after the stimulation was terminated [4]. In addition, concurrent application of tDCS and submental sEMG elevated the baseline of the EMG signal ($\sim$20 $\mu$V) and introduced oscillation due to interference. Lastly, studies exploring the effects of tDCS over M1 found that only stimulation applied prior to motor training, but not concurrent with or after the training, had an effect on corticospinal excitability [47]. However, when cerebellar tDCS was applied during the performance of a limb motor task, differences between online and offline

learning have been demonstrated [6]. These results are contrary to the findings in this study, suggesting that the timing of cerebellar tDCS, applied to an active or passive neural network, might be a crucial variable. Technical solutions to reduce the interference of concurrent tDCS in the EMG signal would be required to test the effects of cerebellar tDCS concurrent with swallowing skill training using submental sEMG.

## Conclusion

In contrast to the hypotheses and the corticospinal literature, both anodal and cathodal cerebellar tDCS inhibited temporal motor skill learning in swallowing. This suggests differences in the effects of cerebellar tDCS on corticobulbar and corticospinal motor functions. Therefore, recent neurophysiological findings on functional differences in the tracts between the cerebellum and the cortex for corticobulbar and corticospinal tasks are supported [34]. A direct comparison of the effects of cerebellar tDCS on neurophysiological and behavioral measures is necessary to receive more insights into the differences between these two systems. Furthermore, polarity-dependent mechanisms in cerebellar tDCS deserve being addressed in future research, as anodal tDCS was not the behavioral inverse of cathodal tDCS, as seen in the limb literature.

The protocol of midline cerebellar tDCS used in this study inhibited motor skill learning in swallowing in healthy individuals. Therefore, this study provides no definitive support for use of tDCS using this protocol to facilitate swallowing skill rehabilitation. Further research is required to confirm this. However, swallowing skill training without tDCS was demonstrated to improve motor performance and motor skill learning in swallowing. This provides a strong indication for future research into the potential implementation of skill training in swallowing rehabilitation.

## Acknowledgements

The assistance of Dr. Karen Ng is gratefully acknowledged.

## Disclosure statement

The researchers working at the University of Canterbury Rose Centre for Stroke Recovery and Research (Christchurch, New Zealand Research) are involved the development of the Biofeedback in Strength and Skill training (BiSSkiT) software which is commercially available.

## Funding

This work was supported by a New Zealand Brain Research Institute Doctoral Scholarship awarded to the first author.

## ORCID

Kerstin L. C. Erfmann http://orcid.org/0000-0002-3770-7830
Richard D. Jones http://orcid.org/0000-0003-2287-3358
Maggie-Lee Huckabee http://orcid.org/0000-0002-8806-7116

## References

[1] Sokolov AA, Miall RC, Ivry RB. The cerebellum: adaptive prediction for movement and cognition. Trends Cogn Sci. 2017;21(5):313–332.

[2] Radman T, Ramos RL, Brumberg JC, et al. Role of cortical cell type and morphology in subthreshold and suprathreshold uniform electric field stimulation *in vitro*. Brain Stimul. 2009;2(4):215–228.e3. http://dx.doi.org/10.1016/j.brs.2009.03.007

[3] Bikson M, Inoue M, Akiyama H, et al. Effects of uniform extracellular DC electric fields on excitability in rat hippocampal slices *in vitro*. J Physiol. 2004;557(1):175–190. http://doi.wiley.com/10.1113/jphysiol.2003.055772

[4] Galea JM, Jayaram G, Ajagbe L, et al. Modulation of cerebellar excitability by polarity-specific noninvasive direct current stimulation. J Neurosci. 2009;29(28):9115–9122. https://www.ncbi.nlm.nih.gov/pubmed/19605648

[5] Galea JM, Vazquez A, Pasricha N, et al. Dissociating the roles of the cerebellum and motor cortex during adaptive learning: the motor cortex retains what the cerebellum learns. Cereb Cortex. 2011;21(8):1761–1770. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3138512/

[6] Cantarero G, Spampinato D, Reis J, et al. Cerebellar direct current stimulation enhances on-line motor skill acquisition through an effect on accuracy. J Neurosci. 2015;35(7):3285–3290. https://www.ncbi.nlm.nih.gov/pubmed/25698763

[7] Oldrati V, Schutter DJLG. Targeting the human cerebellum with transcranial direct current stimulation to modulate behavior: a meta-analysis. Cerebellum. 2018;17(2):228–236. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5849643/

[8] van Dun K, Manto M. Non-invasive cerebellar stimulation: moving towards clinical applications for cerebellar and extra-cerebellar disorders. Cerebellum. 2018;17(3):259–263. https://link.springer.com/article/10.1007%2Fs12311-017-0908-z

[9] Hummel FC, Cohen LG. Non-invasive brain stimulation: a new strategy to improve neurorehabilitation after stroke? Lancet Neurol. 2006;5(8):708–712. http://www.ncbi.nlm.nih.gov/pubmed/16857577

[10] O'Brien A, Bertolucci F, Torrealba-Acosta G, et al. Non-invasive brain stimulation for fine motor improvement after stroke: a meta-analysis. Eur J Neurol. 2018;0:1–10. https://onlinelibrary.wiley.com/doi/abs/10.1111/ene.13643

[11] Wessel MJ, Hummel FC. Review: non-invasive brain stimulation: an interventional tool for enhancing behavioral training after stroke. The Cerebellum. 2018. 17:359–71. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4432668/.

[12] Poortvliet P, Hsieh B, Cresswell A, et al. Cerebellar transcranial direct current stimulation improves adaptive postural control. Clin Neurophysiol. 2017;129(1):33–41.

[13] Kumari N, Taylor D, Signal N. The effect of cerebellar transcranial direct current stimulation on motor learning: a systematic review of randomized controlled trials. Front Hum Neurosci. 2019;13:328.

[14] Roden DF, Altman KW. Causes of dysphagia among different age groups: a systematic review of the literature. Otolaryngol Clin North Am. 2013;46(6):965–987. http://www.ncbi.nlm.nih.gov/pubmed/24262954

[15] Athukorala RP, Jones RD, Sella O, et al. Skill training for swallowing rehabilitation in patients with Parkinson's disease. Arch Phys Med Rehabil. 2014;95(7):1374–1382. http://www.ncbi.nlm.nih.gov/pubmed/24816250

[16] Stepp CE, Britton D, Chang C, et al. Feasibility of game-based electromyographic biofeedback for dysphagia rehabilitation. Proceedings 5th International IEEE/EMBS Conference Neural Engeneering. 2011:p. 233–236.

[17] Martin-Harris B, McFarland D, Hill EG, et al. Respiratory-swallow training in patients with head and neck cancer. Arch Phys Med Rehabil. 2015;96(5):885–893. https://www.sciencedirect.com/science/article/pii/S0003999314012866

[18] Nitsche MA, Liebetanz D, Lang N, et al. Safety criteria for transcranial direct current stimulation (tDCS) in humans. Clin Neurophysiol. 2003;114(11):2220–2222. http://www.ncbi.nlm.nih.gov/pubmed/24980640

[19] Rossi S, Hallett M, Rossini PM, et al. Clinical neurophysiology safety, ethical considerations, and application guidelines for the use of transcranial magnetic stimulation in clinical practice and research. Clin Neurophysiol. 2009;120(12):2008–2039. http://dx.doi.org/10.1016/j.clinph.2009.08.016

[20] Sella O. Skill versus strength in swallowing training: neurophysiological, biomechanical, and structural assessments. Christchurch: University of Canterbury; 2012.

[21] Kantak SS, Winstein CJ. Learning-performance distinction and memory processes for motor skills: A focused review and perspective. Behav Brain Res. 2012;228(1):219–231. http://dx.doi.org/10.1016/j.bbr.2011.11.028

[22] Salmoni AW, Schmidt RA, Walter CB. Knowledge of results and motor learning: a review and critical reappraisal. Psychol Bull. 1984;95(3):355–386. https://psycnet.apa.org/record/1984-22348-001

[23] Brunoni AR, Amadera J, Berbel B, et al. A systematic review on reporting and assessment of adverse effects associated with transcranial direct current stimulation. Int J Neuropsychopharmacol. 2011;14(8):1133–1145. http://www.ncbi.nlm.nih.gov/pubmed/21320389

[24] Bates D, Maechler M, Bolker B. lme4: Linear Mixed-Effects Models Using S4 Classes. R Package Version 0.999999-0. 2012; [cited 2020 Sep 22]. Available from: http://cran.r-project.org/web/packages/lme4/index.html.

[25] Chen J-C, Hämmerer D, D'Ostilio K, et al. Bi-directional modulation of somatosensory mismatch negativity with transcranial direct current stimulation: an event related potential study. J Physiol. 2014;592(4):745–757. https://www.physiology.org/doi/full/10.1152/jn.00645.2011

[26] Herzfeld DJ, Pastor D, Haith AM, et al. Contributions of the cerebellum and the motor cortex to acquisition and retention of motor memories. Neuroimage. 2014;98:147–158. http://www.ncbi.nlm.nih.gov/pubmed/24816533

[27] Jayaram G, Tang B, Pallegadda R, et al. Modulating locomotor adaptation with cerebellar stimulation. J Neurophysiol. 2012;107(11):2950–2957. https://www.physiology.org/doi/full/10.1152/jn.00645.2011

[28] Yavari F, Mahdavi S, Towhidkhah F, et al. Cerebellum as a forward but not inverse model in visuomotor adaptation task: a tDCS-based and modeling study. Exp Brain Res. 2016;234(4):997–1012. https://link.springer.com/article/10.1007/s00221-015-4523-2

[29] Ferrucci R, Marceglia S, Vergari M, et al. Cerebellar transcranial direct current stimulation impairs the practice-dependent proficiency increase in working memory. J Cogn Neurosci. 2008;20(9):1687–1697.

[30] Shah B, Nguyen TT, Madhavan S. Polarity independent effects of cerebellar tDCS on short term ankle visuomotor learning. Brain Stimul. 2013;6(6):966–968. http://www.ncbi.nlm.nih.gov/pubmed/23711765

[31] Woods A, Antal A, Bikson M, et al. A technical guide to tDCS, and related non-invasive brain stimulation tools. Clin Neurophysiol. 2016;127(2):1031–1048.

[32] Buch ER, Santarnecchi E, Antal A, et al. Effects of tDCS on motor learning and memory formation: a consensus and critical position paper. Clin Neurophysiol. 2017;128(4):586–603. https://www.sciencedirect.com/science/article/pii/S1388245717300263

[33] Panouillères MTN, Miall RC, Jenkinson N. The role of the posterior cerebellum in saccadic adaptation: a transcranial direct current stimulation study. J Neurosci. 2015;35(14):5471–5479. http://www.jneurosci.org/content/35/14/5471.short

[34] Jayasekeran V, Rothwell J, Hamdy S. Non-invasive magnetic stimulation of the human cerebellum facilitates cortico-bulbar projections in the swallowing motor system. Neurogastroenterol Motil. 2011;23(9):831–e341. http://www.ncbi.nlm.nih.gov/pubmed/21838728

[35] Daskalakis ZJ, Paradiso GO, Christensen BK, et al. Exploring the connectivity between the cerebellum and motor cortex in humans. J Physiol. 2004;557(Pt 2):689–700. https://physoc.onlinelibrary.wiley.com/doi/full/10.1113/jphysiol.2003.059808

[36] Priori A, Ciocca M, Parazzini M, et al. Transcranial cerebellar direct current stimulation and transcutaneous spinal cord direct current stimulation as innovative tools for neuroscientists. J Physiol. 2014;592(16):3345–3369. http://www.ncbi.nlm.nih.gov/pubmed/24907311

[37] Rampersad SM, Janssen AM, Lucka F, et al. Simulating transcranial direct current stimulation with a detailed anisotropic human head model. IEEE Trans Neural Syst Rehabil Eng. 2014;22(3):441–452. http://www.ncbi.nlm.nih.gov/pubmed/24760939

[38] Parazzini M, Rossi E, Ferrucci R, et al. Modelling the electric field and the current density generated by cerebellar transcranial DC stimulation in humans. Clin Neurophysiol. 2014;125(3):577–584. http://www.ncbi.nlm.nih.gov/pubmed/24176297

[39] Avila E, Geest JVD, Kamga SK, et al. Cerebellar transcranial direct current stimulation effects on saccade adaptation. Neural Plast. 2015;2015:968970. https://www.hindawi.com/journals/np/2015/968970/abs/

[40] Dutta A, Boulenouar RS, Guiraud D, et al. Delineating the effects of anodal transcranial direct current stimulation on myoelectric control based on slow cortical potentials. 36th Annual International Conference IEEE Engineering in medicine and biology society. 2014; p. 3094–9097. Available from: https://ieeexplore.ieee.org/abstract/document/6944277.

[41] Batsikadze G, Moliadze V, Paulus W, et al. Partially non-linear stimulation intensity-dependent effects of direct current stimulation on motor cortex excitability in humans. J Physiol. 2013;591(7):1987–2000.

[42] Jalali R, Miall RC, Galea JM. No consistent effect of cerebellar transcranial direct current stimulation on visuomotor adaptation. J Neurophysiol. 2017;118(2):655–665. http://jn.physiology.org/lookup/doi/10.1152/jn.00896.2016

[43] Ertekin C. Voluntary versus spontaneous swallowing in man. Dysphagia. 2011;26(2):183–192.

[44] Lamvik K, Jones R, Sauer S, et al. The capacity for volitional control of pharyngeal swallowing in healthy adults. Physiol Behav. 2015;152:257–263.

[45] Huckabee ML, Lamvik K, Jones R. Pharyngeal mis-sequencing in dysphagia: characteristics, rehabilitative response, and etiological speculation. J Neurol Sci. 2014; 343(1–2):153–158. http://www.ncbi.nlm.nih.gov/pubmed/24954087

[46] Vigot R. Cerebellar long-term depression: a mechanism for learning and memory. Med Sci. 2003;19(4): 437–441.

[47] Cabral ME, Baltar A, Borba R, et al. Transcranial direct current stimulation: before, during, or after motor training?. Neuroreport. 2015;26(11):618–622.