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Small Enhancement of Bimanual Typing Performance after 20 Sessions of tDCS in Healthy Young Adults

Marta Sevilla-Sanchez,[a] Tibor Hortobágyi,[b] Noa Fogelson,[c] Eliseo Iglesias-Soler,[a] Eduardo Carballeira[a,d] and Miguel Fernandez-del-Olmo[c]*

[a] *Faculty of Sciences of Sport and Physical Education, Department of Physical Education, University of A Coruña, Av. Ernesto Che Guevara 121, Pazos-Liáns, E-15179 Oleiros, A Coruña, Spain*

[b] *University of Groningen, University Medical Center Groningen, Center for Human Movement Sciences, Groningen, The Netherlands*

[c] *Area of Sport Sciences, Faculty of Sports Sciences and Physical Education, Center for Sport Studies, King Juan Carlos University, Madrid, Spain*

[d] *Faculty of Health Sciences, Department of Physiotherapy, Medicine and Biomedical Sciences, University of A Coruña, A Coruña, Spain*

Abstract—Transcranial direct current stimulation (tDCS) is a non-invasive brain stimulation technique that may improve motor learning. However, the long-term effects of tDCS have not been explored, and the ecological validity of the evaluated tasks was limited. To determine whether 20 sessions of tDCS over the primary motor cortex (M1) would enhance the performance of a complex life motor skill, i.e., typing, in healthy young adults. Healthy young adults ($n = 60$) were semi-randomly assigned to three groups: the tDCS group ($n = 20$) received anodal tDCS over M1; the SHAM group ($n = 20$) received sham tDCS, both while performing a typing task; and the Control group (CON, $n = 20$) only performed the typing task. Typing speed and errors at maximum (mTT) and submaximal (iTT) speeds were measured before training, and after 10 and 20 sessions of tDCS. Every subject increased maximum typing speed after 10 and 20 tDCS sessions, with no significant differences ($p > 0.05$) between the groups. The number of errors at submaximal rates decreased significantly ($p < 0.05$) by 4% after 10 tDCS sessions compared with the 3% increase in the SHAM and the 2% increase in the CON groups. Between the 10th and 20th tDCS sessions, the number of typing errors increased significantly in all groups. While anodal tDCS reduced typing errors marginally, such performance-enhancing effects plateaued after 10 sessions without any further improvements in typing speed. These findings suggest that long-term tDCS may not have functionally relevant effects on healthy young adults' typing performance.

Key words: non-invasive brain stimulation, transcranial direct current stimulation (tDCS), motor learning, long-term, motor skills.

INTRODUCTION

Transcranial direct current stimulation (tDCS) is an inexpensive and safe method of neuromodulation used to enhance motor and cognitive functions in healthy adults and patients (Bikson et al., 2016; Antal et al., 2017). By delivering a weak current through the scalp, tDCS can modulate the excitability of the underlying cortical areas. Anodal tDCS modifies the resting membrane potential closer to the critical depolarization threshold, increasing excitability, while the opposite effect of a tonic hyperpolarization is associated with cathodic stimulation (Bindman et al., 1964; Nitsche and Paulus, 2000; Romero Lauro et al., 2014). Pioneering studies reported that tDCS modifications in brain excitability lasted past the stimulation period (Nitsche and Paulus, 2000, 2001) and in combination with motor practice, could enhance motor learning (Nitsche et al., 2003). However, the mechanism of how tDCS might enhance motor performance following motor practice is complex (Stagg and Nitsche, 2011; Kronberg et al., 2017).

Although anodal tDCS may enhance motor learning, only a few of studies have examined the effects of tDCS on motor learning using multiple practice sessions in a task that healthy adults often used in daily life (Reis et al., 2009; Gálvez et al., 2013; Gomes-Osman and Field-Fote, 2013; Ammann et al., 2016; Fan et al., 2017). Animal data from multisession compared with acute use of tDCS suggest that the practice effects last longer and are more stable, possibly due to a cumulative effect produced by the serial sessions (Rueger et al., 2012). Indeed, a meta-analysis of the effect of tDCS on

*Corresponding author. Address: King Juan Carlos University, Faculty of Sports Sciences and Physical Education, Av. de Atenas, s/n, 28922 Alcorcón, Madrid, Spain.
E-mail address: miguel.delolmo@urjc.es (M. Fernandez-del-Olmo).

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manual motor sequence learning reported inconsistent results from single-sessions but a consistent positive effect across multiple sessions (Hashemirad et al., 2016). In addition, in four out of five, multi-session studies, tDCS compared with sham treatment enhanced bimanual motor skill performance (Pixa and Pollok, 2018). The cumulative effect of multiple tDCS sessions is unclear. It could rely on increased cortical modulation across multiple tDCS sessions (Alonzo et al., 2012; Gálvez et al., 2013), although this has not always been the case (Horvath et al., 2016; Zappasodi et al., 2018). Importantly, it is unclear whether changes in cortical plasticity are indicators of changes in motor performance (Abdelmoula et al., 2016; Lopez-Alonso et al., 2018). From a behavioral point of view, the cumulative effects on motor learning may also depend on the task that is being evaluated. In a visual isometric pinch force task, the effects of M1 tDCS on motor learning was limited to the first session (Reis et al., 2009), while in a sequential finger tapping task anodal-tDCS facilitated learning gains (Saucedo-Marquez et al., 2013). Nevertheless, these multisession interventions in healthy participants lasted only up to 5 days and it remains unclear if the benefits of tDCS would incrementally increase with additional sessions of stimulation over weeks, or whether the performance-enhancing effects would plateau over time. In addition, the motor tasks that were evaluated in the above-mentioned studies were highly controlled and their ecological validity and transfer to life skills were limited.

The objective of the present study was to determine whether 20 sessions of tDCS over M1 would enhance the performance of a complex life motor skill, i.e., typing, in healthy young adults. We chose to evaluate typing performance because this is a bimanual motor task that is ubiquitous in young individuals' daily life. Two outcomes can characterize typing performance: typing speed and error. Learning to type on a keyboard with a few or no errors is a complex skill that demands extensive periods of practice and requires the integration of sensory-motor, language, and cognitive skills (Grabowski, 2008; Rosenbaum, 2010). We stimulated M1 because brain imaging data suggest that practicing manual motor sequences induces structural and functional changes in multiple cortical regions such M1, pre-motor cortex, and the supplementary motor area (Hikosaka et al., 2002; Kansaku et al., 2005). Although the underlying mechanisms of motor skill acquisition of a complex motor task remain unclear, M1 seems to play an essential role in the early, rapid phase of motor skill acquisition (Muellbacher et al., 2002; Ehsani et al., 2016; Papale and Hooks, 2018; Yokoi et al., 2018; Hwang et al., 2019). We hypothesized that 20 tDCS sessions applied to M1, in combination with motor practice will improve typing performance compared with motor practice without tDCS. Based on the extant data we further hypothesized that the performance enhancing effects would plateau off after 10 sessions without further improvements in typing performance by session 20. This is the first study to utilize a long-term tDCS intervention in healthy volunteers.

EXPERIMENTAL PROCEDURES

Method

All participants were right-handed (Oldfield, 1971) healthy young adults (n = 63, 42 males, age 21 ± 2 years). Exclusion criteria were: (1) age below 18 or above 30 years; (2) history of neurological diseases, psychological disorders or substance abuse; (3) personal/familial history of epilepsy or fainting; (4) traumatic brain injury, presence of a pacemaker, piece of metal implanted in the skull; (5) current usage of drugs known to influence cognition or behavior; (6) recent (< 6 months) exposure to brain stimulation; (7) disability of the fingers, hands, or wrist, and (8) any experience with typing programs. All participants signed an informed consent, approved by the university ethical committee. The study was conducted according to the declaration of Helsinki (Anon, 2002). Participants were asked to refrain from caffeine or alcohol consumption the day before the experimental sessions.

Design

All the participants completed a familiarization period followed by 23 experimental sessions consisting of three testing and 20 training sessions.

The typing familiarization period began by introducing the instructions of the efficient touch-typing program (Tipp 10 freeware, Thielicke IT Solutions, Berlin, Germany), which is based on the use of both hands and all the fingers (Freeman et al., 2005; Weigelt Marom and Weintraub, 2015). Participants practiced typing a specific text until they were able to use all of the fingers correctly and were at least 70% accurate, without time constraint. Participants reached this criterion in 2–7 training sessions. Next, participants were familiarized in one trial with the two typing tests. All participants completed the familiarization period in 14 days.

Typing performance was tested three times: at baseline (T1), after the 10th (T2) and 20th (T3) session (Fig. 1). Participants were ranked based on baseline maximal typing speed from fastest to slowest and trios of participants were randomly allocated to one of three groups: tDCS, SHAM, or CON. Participants in the tDCS and SHAM groups performed 20 motor training sessions while concurrently receiving anodal or sham tDCS, respectively. Subjects in the CON group performed motor training sessions without stimulation.

The typing training program

The training program consisted of 20 sessions over 2.5 months and was implemented using the testing software (Tipp 10 freeware, Thielicke IT Solutions, Berlin, Germany). Each training session lasted 15 min and was separated by a minimum of 48 h (Fig. 2). The time of day of training was kept constant throughout the 20 sessions for each participant and was similar in the three groups. Participants performed the training and testing sessions in the same laboratory room and with the same equipment.

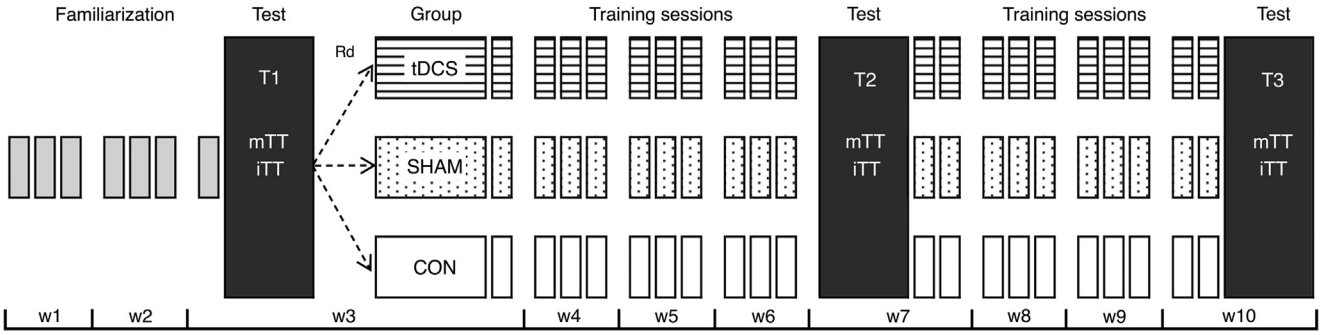

Fig. 1. Experimental protocol. Rd, pseudo-randomized; T1, Time 1; T2, Time 2; and, T3, Time 3; mTT, maximum typing test; iTT, incremental typing test; w, week; w1, week 1; w2, week 2; ….

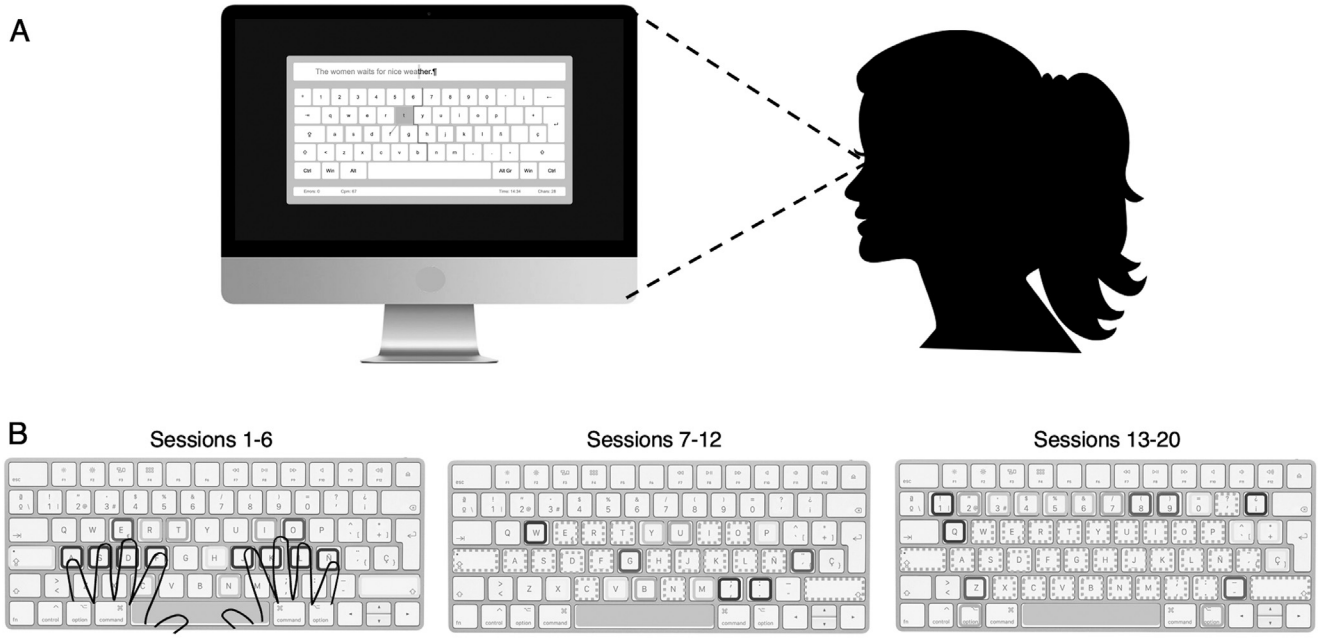

Fig. 2. Typing training program. **(A)** During training sessions participants received visual keyboard feedback on the computer screen. Participants were sitting in a chair in front of a computer screen positioned at eye level and they always used the equal computer model, keyboard and chair; **(B)** touch-typing program and representation of increasing difficulty across the sessions. The correct fingers position, i.e., rest digits 2–5 of each hand on the respective a, s, d, f and h, j, k, l keys of a standard Qwerty keyboard. The software configuration was that regardless of whether participants keystroked the wrong letter, the text continued without demanding correction. The level of difficulty increased session by session by adding new letters to the practice. In the illustration, we can see the representation of the keys that are added after each training session by colours, the darker colours keys are added before. In session 18, participants used all keys, and in sessions 19 and 20, they only used the numeric keypad with their right hand.

Typing tests

Typing skill assessment comprised two tests: the maximum and incremental typing speed tests (mTT, iTT). For mTT, the instructions were: 'Type as fast and accurately as possible'. The text included all of the letters of the Spanish alphabet, a total of 393 characters. The iTT was conducted in order to establish an individual speed–accuracy trade-off function. Participants typed the same text six times at different speeds: 20%, 30%, 40%, 50%, 60%, and 70% of the individual maximum speed obtained in mTT. A metronome was used to pace typing. Instructions were: 'Type as accurately as possible while following the metronome beat'.

tDCS

Anodal tDCS was applied over the left M1 for 15 minutes concurrently with the typing practice. Stimulation intensity was set to 1.5 mA and was delivered for 15 minutes via saline-soaked sponge electrodes (size: 5x5cm; surface area: 25 cm^2; current density: 0.06 mA/cm^2), connected to aDC stimulator (tDCS Stimulator Clinical Version, TCT research Limited, Hong-Kong), using a 10 seconds ''on'' and ''off'' ramping. The configuration of the above parameters was based on a previous study that combined tDCS with physical therapy in patients (Middleton et al., 2014). The size of the anode electrode and stimulation intensity were based on methods detailed previously (Ho et al., 2016). To position the electrodes,

we used a 64-channel EEG cap. The anode electrode was positioned over the C3 electrode site corresponding to the left M1 cortex and the reference cathode electrode was placed over the right supra orbital cortex. Left M1 was the target area of the TDCS stimulation since it has been shown to play an essential role in motor learning (Kansaku et al., 2005; Neva et al., 2014; Beets et al., 2015), seems to improve motor performance in both hands in right-handed participants (Vines et al., 2008), and is the main site of stimulation in previous tDCS motor studies (see review Ref. (Patel et al., 2019)).

Participants in the SHAM group received an initial 30 s of stimulation during which the current linearly increased from 0 to 1.5 mA and then the current was turned off. With this procedure participants are unable to differentiate between real and sham stimulation (Gandiga et al., 2006; Ambrus et al., 2012; Antal et al., 2017). At the end of the last SHAM and tDCS sessions participants were asked to report whether they thought they received stimulation in order to ascertain the efficacy of the sham stimulation.

We followed established safety guidelines (Paneri et al., 2015; Aparicio et al., 2016; Bikson et al., 2016; Nikolin et al., 2018). At the end of each session, we asked each participant to report any adverse effects using a questionnaire (Brunoni et al., 2011). The questionnaire probed the presence of excessive symptoms related to itching, pain, tingling, burning, nausea, fatigue, difficulty of concentration or any other discomfort. Subjects were asked to answer on a scale of 1–4 from lowest to highest, the sensation for each symptom (1 = minimal; 2 = mild; 3 = moderate; 4 = severe).

Behavioral analysis

The dependent variables were speed of typing, i.e., the number of characters [letters and punctuation marks] typed per minute (CPM); and the number of typing errors (incorrect letters or punctuation marks). For the mTT we also calculated a Global Performance Index (GPI) as a measure of typing performance that combined speed and accuracy, based on similar indices from a previous study (Laventure et al., 2016). The GPI was calculated as follows:

$$GPI = e^{-speed} * e^{-accuracy}$$

where e is the mathematical constant, also known as the Euler's number, and is defined as the base of the natural logarithm (∼2.71828). Speed was the average time between correct keypresses in seconds. The accuracy was the relationship between the number of correct answers with respect to the total number of answers (e.g., 100% of accuracy = 1). The higher GPI values indicate better typing performance.

For iTT, we calculated the number of errors at each speed and the total number of errors as the sum of errors performed in each speed. For the adverse effects tDCS-induced questionnaire, we calculated the total mean of responses to the eight variables (itching, pain, tingling, burning, nausea, fatigue, difficulty of concentration, discomfort) across the 20 sessions.

Statistical analyses

Data are presented as mean ± standard deviation (± SD). Normality was assessed using the standard distribution, visual inspection of Q–Q plots and box plots, and the Shapiro–Wilk test. We evaluated the homoscedasticity using Levene's test.

The tDCS-induced sensations were analyzed using an independent samples t-test.

The tDCS effects were assessed using the typing speed, number of errors, and GPI scores. Changes within and between groups for the typing speed, errors and GPI scores, in the mTT test and the total number of errors in the iTT test, were compared using mixed models for repeated measures designs. We utilized Jamovi software (AA.VV., 2020), the GAMLj module (Gallucci, 2019), and the lme4 R package (R, 2018). GAMLj estimates variance components with restricted (residual) maximum likelihood (REML), which produces unbiased estimates of variance and covariance parameters. The inter-subject factor group (tDCS, SHAM, CON), the intra-subject factor time (T1, T2 and T3) and the interaction (group × time) were set as fixed effects. The participant intercept was set as the random effect. Bonferroni-Holm were performed to correct for multiple comparisons. Furthermore, in the iTT test since there were significant differences in the total number of errors at T1, this variable was included as a covariable in the subsequent analyses of the mixed model.

The β coefficients and their corresponding 95% confidence intervals represented the effect size. In order to evaluate the relationship between the changes in speed and accuracy and the enhancement in motor skill, we evaluated the Speed–Accuracy Tradeoff Function using the errors at 20%, 30%, 40%, 50%, 60%, and 70% of the individual maximum speed for the iTT test, using a previously published procedure (Reis and Fritsch, 2011).

The alpha level was set at $p < .05$.

RESULTS

Of the original 63 participants, three dropped out: one due to a wrist injury and two participants performed the study protocol incorrectly. The remaining 60 participants (n = 20 per group) completed all the sessions.

A total of 800 tDCS sessions were performed without complications. All participants in the tDCS and SHAM groups occasionally experienced mild and transient adverse effects during stimulation, such as "itching", "burning" or "discomfort". Transient erythema (∼5 min) appeared in 7% of participants (tDCS: 2; SHAM: 1), due to the saline-soaked sponge, in participants with atopic or sensitive skin. Two participants reported a mild headache once. In no session was it necessary to interrupt the stimulation for any reason. Overall, tDCS-induced self-reported adverse effects were minimal (tDCS: 1.21 ± 0.15 vs. Sham: 1.18 ± 0.11) and were not significantly different between groups (t_{39} = 1.17, p = 0.251) (Table 1).

In the tDCS and SHAM groups, 55% and 53% of participants reported that they were being stimulated,

Table 1. Adverse effects tDCS-induced. Stimulation sensations self-reported by the participants after each training session across the time. Stimulation sensations were assessed on a Likert 4-point scale: 1 = minimal; 2 = mild; 3 = moderate; 4 = severe

Sensations							
Itching	Painful	Tingling	Burning	Nauseous	Fatigue	Difficulty of concentration	Discomfort
tDCS							
1.77	1.12	1.25	1.24	1.01	1.15	1.09	1.02
(0.44)	(0.17)	(0.32)	(0.29)	(0.02)	(0.34)	(0.24)	(0.07)
Sham							
1.69	1.14	1.25	1.12	1.02	1.12	1.12	1.07
(0.35)	(0.18)	(0.28)	(0.17)	(0.06)	(0.20)	(0.21)	(0.22)

Note: Data are Mean (SD).

respectively, confirming the blinding procedure of the SHAM group.

Maximum typing test (mTT)

For the mTT, there was a main effect for Time ($F_{2,113}$ = 88.20, p < .001). There were no significant Group or Time*Group interaction effects (Fig. 3). The average typing speed in all the participants was 165 ± 55 CPM at T1, 214 ± 52 CPM at T2 ($\Delta_{T2\text{-}T1}$ = 49 CPM), and 253 ± 52 CPM at T3 ($\Delta_{T3\text{-}T1}$ = 88 CPM) (p_{holm} < 0.01 across the comparisons, β = 50 and $CI_{95\%}$ = 37 to 63; β = 88 and $CI_{95\%}$ = 75 to 101; β = 39 and $CI_{95\%}$ = 26 to 52, for T1 vs T2, T1 vs T3 and T2 vs T3, respectively).

There were no significant Time, Group, or Time*Group effects in the number of errors (Table 2).

In the GPI scores, there was a main effect for Time ($F_{2,114}$ = 36.35, p < .001). There were no significant Group or Time*Group interaction effects. The mean GPI scores in all participants were 0.27 ± 0.04 at T1, 0.29 ± 0.03 at T2, and 0.30 ± 0.02 at T3 (p_{holm} < 0.01 across the comparisons, β = 0.02 and $CI_{95\%}$ = 0.02 to 0.03; β = 0.04 and $CI_{95\%}$ = 0.03 to 0.05; β = 0.01 and $CI_{95\%}$ = 0.01 to 0.02, for T1 vs T2, T1 vs T3 and T2 vs T3, respectively).

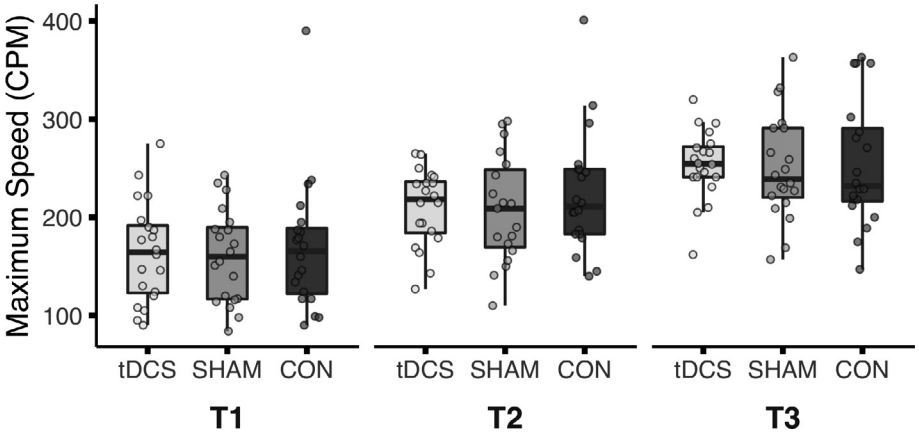

Fig. 3. Speed in the maximum typing test (mTT). The evolution of maximal typing speed across the evaluations. Dots beyond the whiskers represent outliers in the data set. Pair comparison with Holm-Bonferroni adjustment Time effect, p < .01.

Incremental typing test (iTT)

For the total number of errors, there was a main effect of Time ($F_{2,1012}$ = 14.70, p < .001) and a Time*Group interaction ($F_{4,1012}$ = 4.99, p < .001) but no Group effect (Fig. 4A). The total number of errors decreased in the tDCS group between T1 and T2 (β = −4.19, $CI_{95\%}$ = −5.56 to −2.82, t_{3003} = 5.99, p_{holm} < 0.001) and increased in the SHAM and CON groups (β = 2.63, $CI_{95\%}$ = 1.27 to 4, t_{3003} = 3.78, p_{holm} < 0.004; β = 2.19, $CI_{95\%}$ = 0.82–3.56, t_{3003} = 3.13, p_{holm} < 0.04, respectively). Thus, errors decreased only in the tDCS group after 10 sessions ($tDCS_{\Delta T2\text{-}T1}$: −4.19 vs. $Sham_{\Delta T2\text{-}T1}$: 2.63 and, vs. $CON_{\Delta T2\text{-}T1}$: 2.19). From T2 to T3, the total number of errors increased across all the groups (β = 3.95, $CI_{95\%}$ = 1.13–6.79, t_{3003} = 5.65, p_{holm} < 0.001; β = 4.77, $CI_{95\%}$ = 1.95–7.59, t_{3003} = 6.84, p_{holm} < 0.001; β = 2.63, $CI_{95\%}$ = 0.19–5.46, t_{3003} = 3.81, p_{holm} = 0.004; for tDCS, Sham and Control, respectively). At T1 the total number of errors was higher in the tDCS compared to the SHAM group (β = 5.46, $CI_{95\%}$ = 0.83–10.09, t_{274} = –268, p_{holm} < 0.001), without significant differences between the groups at T2 and T3.

To control for the differences in the total number of errors between groups at T1, we introduced the total number of errors at T1 as a covariant of a mixed model (Fig. 4B). There were significant Time ($F_{1,625}$ = 31.14, p < .001) and Group ($F_{2,56}$ = 4.98, p = .01) main effects but no Time*Group interaction. Post hoc analysis confirmed the effect identified by the model, i.e., reductions in error only after tDCS but not after SHAM or CON (β = −4.16, $CI_{95\%}$ = 1.22–7.10, t_{56} = −2.78, p_{holm} = 0.02; β = −4.00, $CI_{95\%}$ = 1.12–6.88, t_{56} = −2.72, p_{holm} = 0.02; and, β = 0.17, $CI_{95\%}$ = −2.71 to 3.03, t_{56} = 0.11, p_{holm} = 0.91, for tDCS vs SHAM, tDCS vs CON, and SHAM vs CON respectively). From T2 to T3, the total number of errors increased in all the groups (β = −3.79,

Table 2. Number of errors in the maximum typing test (mTT). Descriptive data and ANOVA results of the number of errors in mTT

Time	Group			*p*-value		
	tDCS	SHAM	CON	Time	Group	Time X Group
T1	33 ± 31	22 ± 18	21 ± 14			
T2	24 ± 23	17 ± 14	21 ± 22	0.29	0.22	0.77
T3	26 ± 17	21 ± 16	18 ± 15			

Note: Data are Mean ± SD.

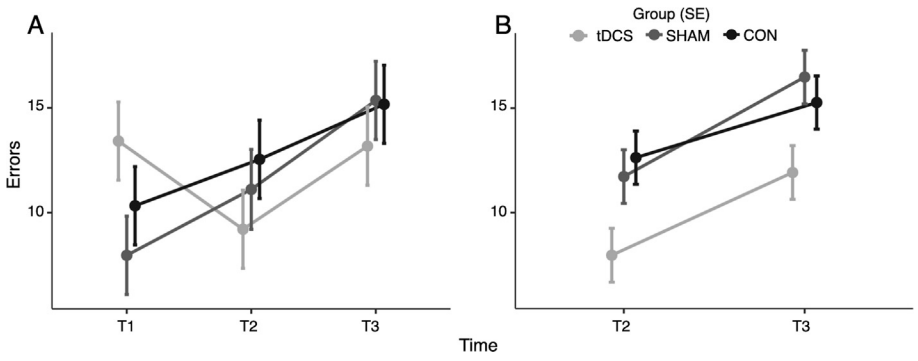

Fig. 4. Total number of errors in the incremental typing test (iTT). **(A)** The total number of errors across the three evaluations. **(B)** The total number of errors at T2 and T2 with T1 as covariable. See results section for a detail information of the significant effects reported by the ANOVA **(A)** and ANCOVA **(B)**. Data are Mean ± 95% confidence interval (CI).

$CI_{95\%} = -2.46$ to -5.13, $t_{625} = -5.58$, $p_{holm} < 0.001$).

We were unable to characterize the Speed–Accuracy Tradeoff Function. As Fig. 5 shows there was a high inter-individual variability in the speed-accuracy relationship and only T3 showed a clear sigmoid fit across the groups.

DISCUSSION

The purpose of the present study was to determine whether 20 sessions of tDCS delivered to the M1 would enhance the performance of a complex motor skill, namely, typing, in healthy young adults. We found that anodal tDCS significantly reduced the total number of errors during an incremental typing test (iTT) but showed no effect on the maximal typing speed. As hypothesized, the tDCS effects were pronounced during the first 10 sessions.

To our knowledge, the present study is the first to deliver tDCS for 20 sessions in an effort to improve the performance of a life-skill in healthy young adults. We found that after 20 sessions of tDCS, participants performed iTT with 6% fewer errors compared to the SHAM and control groups. Our data agree with previous findings demonstrating favorable effects of tDCS on acquiring a bimanual motor skill (Pixa and Pollok, 2018). Gomes-Osman and Field-Fote (2013) employed a modified version of the typing task and reported that five sessions of bi-hemispheric anodal tDCS improved typing performance.

In the present study, stimulation targeted M1 and its typing error-reducing effects were prominent after 10 sessions only in the tDCS group. These findings are consistent with the role of M1 in the early stages of motor skill acquisition (Muellbacher et al., 2002; Beets et al., 2015; Kawai et al., 2015; Buch et al., 2017; Yokoi et al., 2018; Broeder et al., 2019). Findings in rats suggest that M1 plays an active role in motor skill acquisition up to 9 days, after which M1 can become disengaged from movement control (Hwang et al., 2019). In the present study M1 plasticity, may have been the underlying mechanism for the coding of the motor skill into motor memory, during the initial 10 sessions of the typing practice (Dayan and Cohen, 2011; Ostry and Gribble, 2016).

Somewhat unexpectedly, the number of errors in iTT started to increase after the 10th session in all three groups, so that the number of typing error was still lower in tDCS compared with SHAM and CON. One possible explanation is that the participants typed increasingly faster, thus committing more errors. In the current study the performance-enhancing effects of tDCS stimulation seemed to reach a plateau and did not facilitate typing performance beyond the level reached at session 10. In other words, the effects of tDCS stimulation were not linear or cumulative. Stimulation may have helped maintain the gains achieved during the initial 10 sessions, however this is merely a speculation which cannot be compared with prior data, as studies to date only completed five sessions of stimulation at most (Alonzo et al., 2012; Gálvez et al., 2013; Ho et al., 2016).

The favorable effects of anodal stimulation over M1 after five sessions have also motivated us to assess the stimulation effects on a speed-accuracy tradeoff during typing (Reis et al., 2009). However due to large inconsistencies within individual trade-accuracy relationships, we were unable to compute individual curve fits across sessions and examine stimulation effects on the tradeoff. Participants only showed a sigmoidal speed-accuracy tradeoff relationship at T3, although the inter-subject variability remained high. This variability may reflect the complexity of the iTT assessment and may explain why previous typing studies chose to report speed and accuracy measures separately instead of using a trade-off function (Rosenbaum, 2010; Kalava et al., 2014; Weigelt Marom and Weintraub, 2015).

The positive effects of anodal tDCS were limited to the iTT and were not observed with the mTT. During the mTT,

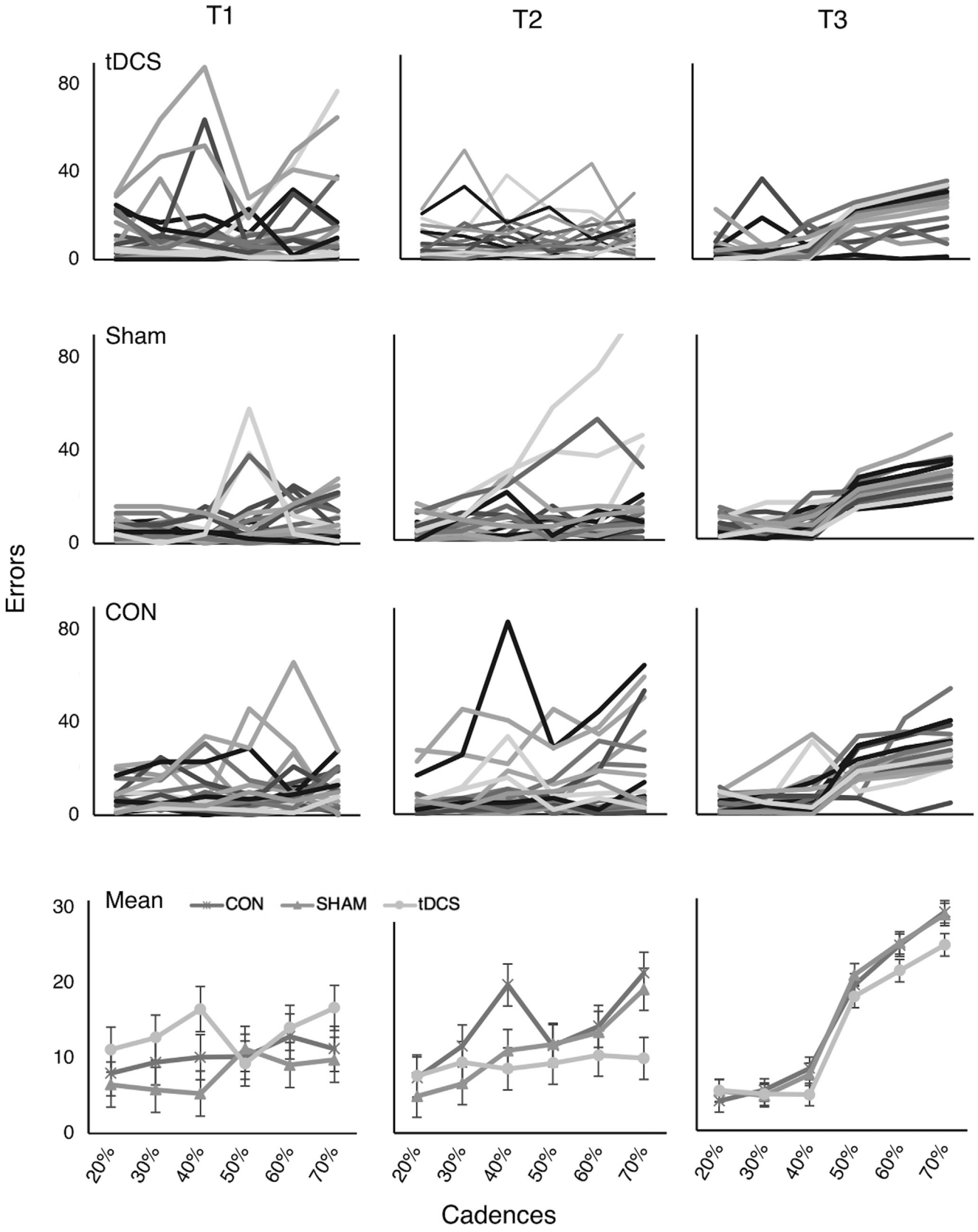

Fig. 5. Speed-accuracy curves for iTT. Errors at 20, 30, 40, 50, 60, 70% of maximal typing speed. The last panel shows Mean ± 95%C.I.

participants increased typing speed by 67%, keeping the number of errors stable across the 20 training sessions without showing significant differences between groups. The continued improvements in speed across the 20 sessions clearly rule out a celling effect in mTT. These results were expected as numerous studies reported continuous improvements in writing speed over 100 hours or even years of practice (Chapman, 1919, Keith and Ericsson, 2007). Both outcomes, iTT and mTT, demand asynchronous bilateral well-coordinated and skilled finger movements. However, in the iTT the metronome sets typing speed, while in the mTT participants were able to freely select their execution speed. Our mTT data suggest that the participants seemed to have developed a cognitive strategy to increase the maximum typing speed, as long as it allowed them to keep errors constant. Previous studies have also noticed this typing strategy (Rosenbaum, 2010; Weigelt-Marom and Weintraub, 2018). In contrast, during the iTT the speed was set, increasing the cognitive demands compared to mTT. This is in line with other studies suggesting that tDCS stimulation is preferentially effective in tasks that require high cognitive demand (Horvath et al., 2016; Lum et al., 2018), accounting for the effects we observed after real stimulation on iTT but not on mTT. Collectively, the findings suggest that the effects of anodal tDCS may be task dependent (Kantak et al., 2012; Saucedo-Marquez et al., 2013).

We observed minimal adverse effects of tDCS, and these were similar across the tDCS and sham stimulation groups, suggesting that repeated sessions of tDCS with the parameters used in the present study, are safe in healthy young adult participants. These findings expand evidence from previous studies related to the safety of repeated sessions of tDCS (Nikolin et al., 2018).

Our study has several limitations. The first was a lack of a follow-up of typing performance. We chose typing as the motor task because it has a high ecological validity in everyday life and is thus functionally relevant, also facilitating adherence. However, for this reason it was impossible to ask the participants to refrain from typing in order to assess the retention effects of the stimulation. In addition, we were unable to control for the amount of typing participants might have performed outside the study. However, since all the participants were university students belonging to the same academic group, it is unlikely that there were systematic differences between groups in the practice time outside of the experiment. In addition, the effects of tDCS might have been limited by the stimulation of a single cortical area. In fact, our results suggest a potentially diminishing role of anodal tDCS over M1 in motor learning across 20 sessions of stimulation. Thus, future studies using other stimulation sites are warranted in order to minimize a possible plateau in motor performance. Additionally, a positive control group having tDCS applied to a region that is not expected to influence the dynamics of motor learning, will shed further light on the enhanced learning effects attributed to tDCS. Another potential limitation in our study is the absence of neurophysiological measures. Future studies using combined TMS and EEG techniques are warranted in order to further explore the underlying mechanisms that may contribute to tDCS induced enhancements.

Our findings question the functionality of tDCS effects on typing performance in healthy participants because the effect size of the observed improvements induced by real tDCS were small for iTT and absent for mTT. However, it is possible that the effects would have been more pronounced in patients with lower baseline typing performance due to a motor deficit.

In conclusion, while anodal tDCS over M1 reduced typing errors marginally, the performance-enhancing effects plateaued after 10 sessions, showing no significant improvements in typing speed. Our findings question the efficacy of tDCS for enhancing healthy young adults' typing performance by functionally meaningful margins.

FINANCIAL DISCLOSURES

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COMPETING INTEREST

None.

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