Reduction of Dual-task Costs by Noninvasive Modulation of Prefrontal Activity in Healthy Elders

Brad Manor[1,2,3], Junhong Zhou[4], Azizah Jor'dan[1,2,3], Jue Zhang[4], Jing Fang[4], and Alvaro Pascual-Leone[2,3]

Abstract

■ Dual tasking (e.g., walking or standing while performing a cognitive task) disrupts performance in one or both tasks, and such dual-task costs increase with aging into senescence. Dual tasking activates a network of brain regions including pFC. We therefore hypothesized that facilitation of prefrontal cortical activity via transcranial direct current stimulation (tDCS) would reduce dual-task costs in older adults. Thirty-seven healthy older adults completed two visits during which dual tasking was assessed before and after 20 min of real or sham tDCS targeting the left pFC. Trials of single-task standing, walking, and verbalized serial subtractions were completed, along with dual-task trials of standing or walking while performing serial subtractions. Dual-task costs were calculated as the percent change in markers of gait and postural control and serial subtraction performance, from single to dual tasking. Significant dual-task costs to standing, walking, and serial subtraction performance were observed before tDCS ($p < .01$). These dual-task costs were less after real tDCS as compared with sham tDCS as well as compared with either pre-tDCS condition ($p < .03$). Further analyses indicated that tDCS did not alter single task performance but instead improved performance solely within dual-task conditions ($p < .02$). These results demonstrate that dual tasking can be improved by modulating prefrontal activity, thus indicating that dual-task decrements are modifiable and may not necessarily reflect an obligatory consequence of aging. Moreover, tDCS may ultimately serve as a novel approach to preserving dual-task capacity into senescence. ■

INTRODUCTION

Standing and walking require a host of cognitive functions, from volition and attention to STM and decision-making (Yogev-Seligmann, Hausdorff, & Giladi, 2008). Healthy young adults are able to maintain these activities while simultaneously performing additional cognitive tasks, for instance, talking, reading, or navigating an unfamiliar environment (Prado, Stoffregen, & Duarte, 2007). In older adults, such "dual tasking" often comes at a cost to performance in one or both tasks (Schwenk, Zieschang, Oster, & Hauer, 2010; Hausdorff, Schweiger, Herman, Yogev-Seligmann, & Giladi, 2008; Camicioli, Howieson, Lehman, & Kaye, 1997; Lundin-Olsson, Nyberg, & Gustafson, 1997). Aging therefore appears to reduce one's capacity to differentially recruit the required brain networks or enlist the alternative cognitive strategies needed to maintain performance in both tasks (Tucker & Stern, 2011; Stern, 2002; Pashler, 1994). Neuroimaging evidence indicates that performing more demanding cognitive tasks requires more intense activation within recruited brain networks (Toepper et al., 2014; Meinzer, Lindenberg, Antonenko, Flaisch, & Flöel, 2013; Duncan & Owen, 2000; MacDonald, Cohen, Stenger, & Carter, 2000) and/or recruitment of alternative networks (Hampson, Driesen, Skudlarski, Gore, & Constable, 2006; Cabeza, 2002). Performing two cognitive tasks concurrently—as compared with separately—activates additional brain regions including the left pFC (Deprez et al., 2013). Strategies designed to facilitate left pFC excitability may therefore improve dual-task capacity and thus help to maintain functional performance into senescence.

Transcranial direct current stimulation (tDCS) passes low-amplitude electrical current between two or more electrodes placed on the scalp. A portion of this current penetrates the skull and induces changes in brain tissue polarity and thus its excitability (Nitsche & Paulus, 2000; Priori, Berardelli, Rona, Accornero, & Manfredi, 1998). tDCS targeting the left pFC acutely improves both cognitive and motor functions, including working memory (Fregni et al., 2005), problem solving (Metuki, Sela, & Lavidor, 2012), decision-making (Hecht, Walsh, & Lavidor, 2010), and movement accuracy during reaching tasks (Reis & Fritsch, 2011). We therefore hypothesized that tDCS targeting the left pFC would minimize the dual-task costs induced by performing a secondary cognitive task while standing and walking in older adults.

METHODS

Participants

Thirty-seven healthy older adults were recruited and provided written informed consent as approved by the

[1]Hebrew SeniorLife, Boston, MA, [2]Beth Israel Deaconess Medical Center, Boston, MA, [3]Harvard Medical School, [4]Peking University, Beijing, China

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institutional review board of Peking University First Hospital, Beijing. All participants were right-handed as determined by the Edinburgh Handedness Inventory. Exclusion criteria included any acute medical condition requiring hospitalization within the past 6 months; the use of centrally acting medication; and any self-reported cardiovascular disease, neurological disease, musculoskeletal disorder, or any other condition that may influence physical function.

Protocol

Each participant completed two study visits separated by 1 week at approximately the same time of day. On each visit, a dual-task paradigm was completed immediately before and after a seated session of real or sham (placebo) tDCS (see the following section for details). Each dual-task assessment was composed of multiple trials of single and dual tasking, including (1) undisturbed walking (single task), (2) undisturbed standing (single task), (3) counting backward while seated (single task), (4) walking while counting backward (dual task), and (5) standing while counting backward (dual task). Walking trials consisted of a 50-m walk at preferred speed along a custom-built, straight walkway instrumented with force sensors. Participants were instructed to walk at their normal pace before each trial. Standing trials consisted of 60 sec of eyes-open standing on a stationary force platform. Participants were instructed to stand as still as possible throughout the trial. The counting task consisted of verbalized serial subtractions of 7 from a random, three-digit number. We chose this task because it is the most commonly employed task within this type of dual-task paradigm and it significantly diminishes performance in numerous markers of both gait and postural control (Zhou et al., 2014). Trial order was randomized at each visit. Within dual-task trials, no specific instructions were given regarding task prioritization.

tDCS

tDCS was delivered with a battery-powered electrical stimulator (Chattanooga Ionto Iontophoresis System) connected to a pair of saline-soaked 35-cm^2 synthetic surface sponge electrodes placed on the scalp. The positive electrode (i.e., anode) was placed over the F3 region of the 10–20 EEG electrode placement system, and the negative electrode (i.e., cathode) was placed over the right supraorbital margin (Boggio et al., 2008). The real tDCS condition consisted of 20 min of continuous stimulation at a maximum intensity of 2.0 mA. At the beginning of stimulation, the current was increased manually from 0.1 mA, in 0.1-mA increments over a 30-sec period. Participants were instructed to notify the investigator if and when they felt any uncomfortable sensations arising from the stimulation. The ramp-up procedure was stopped at this point, and for the remainder of the session, tDCS was delivered at an intensity of 0.1 mA below the highest level reached. At the end of the session, current was automatically ramped down to 0.0 mA over a 30-sec period. For sham tDCS, the same electrode montage, ramp-up procedure, and session duration were used; however, current was automatically ramped down 60 sec after completion of the ramp-up procedure. This is a reliable control as sensations arising from tDCS diminish considerably after the first minute of stimulation (Gandiga, Hummel, & Cohen, 2006). Participants were blinded to tDCS condition, and tDCS was administered by study personnel uninvolved in any other study procedure. At the end of each visit, participants completed a short questionnaire (Brunoni et al., 2011) to assess potential side effects. They were also asked to state if, in their opinion, they received real or sham stimulation on that day.

Data Analysis

Standing performance was quantified by the average speed and area of postural sway, recorded by the force plate as center-of-pressure fluctuations beneath the feet (Manor et al., 2010). Walking performance was quantified by average gait speed and stride duration variability (i.e., the standard deviation about the mean duration of consecutive heel strikes; Zhou et al., 2014; Hausdorff, Rios, & Edelberg, 2001). Performance in the counting task was quantified by the percentage of correct responses within each trial. Dual-task costs to each outcome were then calculated with the following formula: [(dual-task performance − single task performance) / single task performance] × 100 (Zhou et al., 2014; Manor et al., 2010; Schwenk et al., 2010).

Statistical Analysis

Descriptive statistics were used to summarize group characteristics and all primary and secondary study outcomes. One-sample t tests were used to determine if baseline (i.e., pre-tDCS) dual-task costs to each study outcome were significantly different from zero. The efficacy of tDCS blinding was examined using Fisher's exact test to determine if participant guesses of tDCS condition (during Visit 2) were correct to a greater degree than that expected because of chance. The effect of tDCS on the dual-task cost to each outcome was analyzed using 2 × 2 repeated-measures ANOVAs. Model effects included tDCS condition (real, sham) and Time (pre-tDCS, post-tDCS) and their interaction. Study outcomes obtained from each condition were analyzed with a separate model. Significance level was set to $p = .05$ for all analyses. Tukey's post hoc testing was completed on significant models to identify differences between variable means within each tDCS condition and time point combination. Similar ANOVA models and post hoc testing (where appropriate) were also used to examine the effects of tDCS on each study outcome separately within single- and dual-task conditions.

For those models in which real tDCS significantly altered a given study outcome, Pearson's correlation analyses were used to examine the relationship between tDCS intensity and change in study outcome from pre- to post-tDCS. The significance level was set to $p = .05$ for all analyses.

RESULTS

Cohort Characteristics

Thirty-seven participants (12 men and 25 women; mean ± *SD*: age = 61 ± 5 years, weight = 71 ± 9 kg, height = 1.7 ± 0.1 m) were recruited and completed all study procedures. No adverse events were reported throughout the study. The intensity of tDCS, which was determined separately for each participant at each study visit (see Methods section), did not significantly differ between visits ($p = .91$). Average tDCS intensity across all participants was 1.4 ± 0.4 mA (range = 0.8–2.0 mA). Participant blinding procedures were sufficient, as guesses of tDCS condition were not correct more than that expected because of chance ($p = .29$).

Dual-task Costs to Standing, Walking, and Serial Subtraction Performance

Before the administration of tDCS, all measured dual-task costs were greater than zero ($p < .01$). As compared with the single-task standing condition, performing serial subtractions while standing resulted in a 45 ± 23% increase in postural sway area and a 40 ± 19% increase in postural sway velocity. As compared with the single-task walking condition, performing serial subtractions while walking induced a 13 ± 7% decrease in gait speed and a 28 ± 21% increase in stride time variability.

Dual tasking also resulted in a significant cost to serial subtraction performance ($p = .01$) before the administration of tDCS. The magnitude of this cost was similar between testing days. When averaged across the testing days, the percentage of correct responses was 96 ± 7% when the task was performed within the single-task condition (i.e., seated). As compared with this condition, performance was 3.1 ± 2.0% worse when the task was done while walking. Standing did not significantly disrupt serial subtraction performance; however, neither standing nor walking altered the total number of responses that was given during each trial.

The Effects of tDCS on the Dual-task Costs to Standing and Walking

Figure 1 illustrates the dual-task costs to standing postural sway area in a representative participant, which were noticeably less after real as compared with sham tDCS.

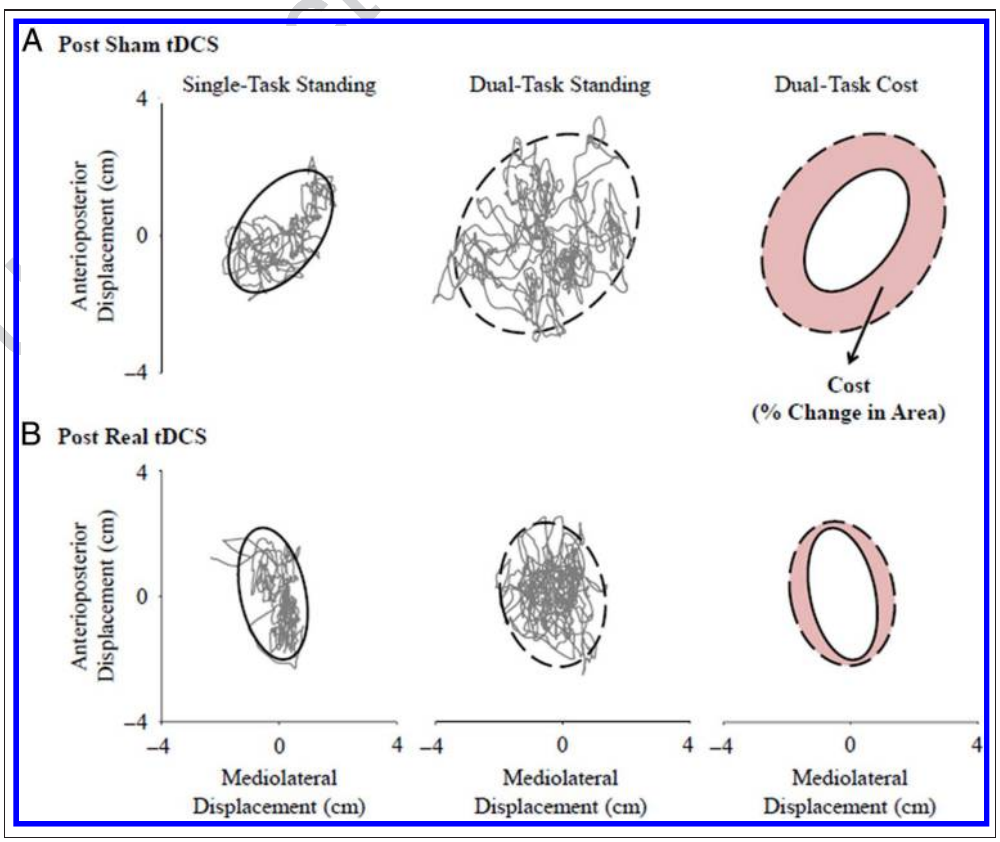

Figure 1. The cost of performing a cognitive task on standing postural control after real and sham tDCS in a representative participant. Standing postural control was assessed by using a force plate to record postural sway, as indicated by transverse-plane fluctuations in center of pressure over a 1-min period. Participants completed trials of single-task standing (i.e., standing quietly with eyes open) as well as dual-task standing (i.e., standing while performing an unrelated cognitive task). The unrelated cognitive task consisted of verbalized serial subtractions of 7 from a random three-digit number. For each trial, the magnitude of postural sway was quantified by calculating the area of an ellipse enclosing 95% of the sway trajectory. The dual-task cost was defined by the percent change in postural sway area between single- and dual-task conditions. For this participant, the cognitive dual-task cost to sway area was noticeably less after real (B) tDCS as compared with the sham or placebo (A) condition. A similar paradigm was used to examine the effects of dual tasking on postural sway speed as well as outcomes related to walking (not pictured).

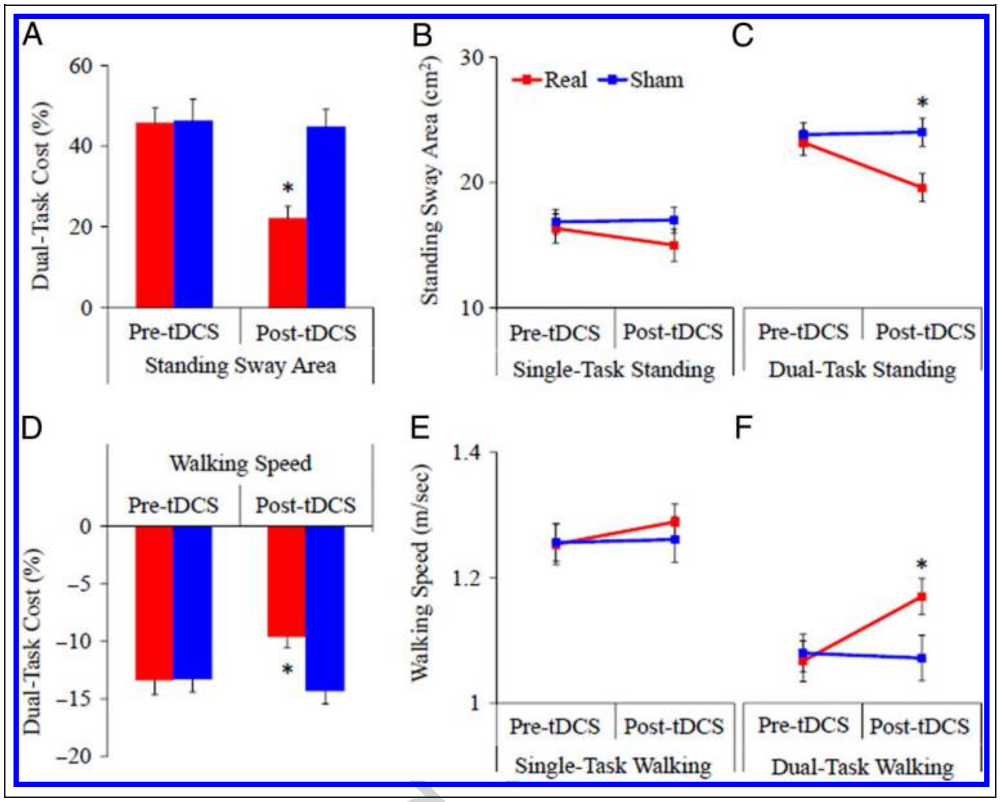

Figure 2. The dual-task costs to standing and walking before and after tDCS. As compared with sham tDCS, real tDCS reduced the dual-task cost to standing postural sway area (A) and velocity (not pictured) as well as walking speed (D). Further analysis revealed that neither real nor sham tDCS influenced standing postural sway area or walking speed under single-task conditions (B and E). Under dual-task conditions, however, standing sway area and velocity (not pictured) were smaller and slower, and walking speed was faster—yet only after real tDCS (C and F). Error bars reflect standard error. Within each panel, an asterisk (*) indicates that the corresponding mean value was significantly different from all other factor means, as determined by Tukey's post hoc testing of significant tDCS condition (real, sham) × Time (pre-tDCS, post-tDCS) interactions within repeated-measures ANOVA models. Means without an asterisk were not different from one another.

The effects of tDCS on the dual-task costs to selected measures of both standing and walking in the entire cohort are presented in Figure 2. Repeated-measures ANOVAs revealed significant interactions between tDCS condition (real, sham) and Time (pre-tDCS, post-tDCS) for the dual-task cost to postural sway area (F = 4.5, p = .01; Cohen's d = 0.50; Figure 2A), postural sway speed (F = 3.9, p = .03; Cohen's d = 0.45), and gait speed (F = 6.7, p = .01; Cohen's d = 0.61; Figure 2D). Post hoc testing indicated that, for each of these variables, the dual-task cost was less after real tDCS as compared with sham tDCS as well as compared with either baseline condition. No significant correlations were present between tDCS intensity and the absolute or percent change in postural sway area, postural sway speed, or gait speed from pre to post real tDCS. tDCS did not influence the dual-task costs to stride time variability when walking.

To further understand the effects of tDCS on the dual-task costs to standing and walking, we subsequently examined the effects of tDCS on standing and walking outcomes within single- and dual-task conditions separately. Neither real nor sham tDCS influenced any standing or walking metric under single-task conditions (see Figure 2B and E). Within the dual-task condition, however, repeated-measures ANOVAs revealed significant interactions between tDCS condition and Time for postural sway area (F = 6.4, p = .01; Cohen's d = 0.59; Figure 2C), postural sway speed (F = 4.8, p = .02; Cohen's d = 0.52), and gait speed (F = 6.7, p = .01; Cohen's d = 0.61; Figure 2F). Postural sway speed and area were lower, and gait speed was faster, after real tDCS as compared with sham tDCS as well as compared with either baseline condition.

The Effects of tDCS on the Dual-task Cost to Serial Subtraction Performance

Real tDCS also effectively mitigated the cost of walking to performance on the arithmetic task. Repeated-measures ANOVAs revealed an interaction between tDCS condition (real, sham) and Time (pre-tDCS, post-tDCS) for the walking-induced cost to serial subtraction error rate (F = 6.8, p = .01; Cohen's d = 0.62; Figure 3A). Tukey's post hoc testing indicated that this cost was less after real tDCS as compared with sham tDCS and with both pre-tDCS values. The absolute or relative magnitude of the reduction in this dual-task cost after real tDCS was not correlated with the intensity of administered tDCS.

Further analysis indicated that tDCS influenced error rates while walking, yet not while sitting. Specifically, repeated-measures ANOVA revealed an interaction between tDCS condition and Time for error rate within walking trials (F = 6.7, p = .01; Cohen's d = 0.61; Figure 3D). Post hoc testing indicated that the error rate within walking trials was lower after real tDCS as compared with sham tDCS and both baseline conditions. On the other hand, neither real nor sham tDCS altered error rates when sitting (Figure 3B).

tDCS did not affect the standing dual-task cost to arithmetic performance (Figure 3C).

DISCUSSION

A single 20-min session of tDCS with the anode over the left pFC significantly reduced the dual-task costs induced by performing mental arithmetic while standing and walking. This observation demonstrates that the capacity to dual task is not a fixed characteristic but in fact modifiable in older age and dependent on activity of specific brain networks that include, or are reachable by, the left pFC.

The observed magnitude of dual-task costs at baseline (i.e., before real or sham tDCS) is consistent with those found by previous studies (Manor et al., 2010; Hausdorff et al., 2008) and confirms that older adults, even when healthy, fail to sustain performance under dual-task conditions of heightened cognitive demand. Importantly, tDCS did not alter standing, walking, or serial subtraction performance within single-task conditions. The tDCS-induced reduction in dual-task costs was instead spurred by improved performance specifically within dual-task conditions. The observation that tDCS did not alter task performance within single-task conditions suggests that the individual task demands of standing, walking, and mental arithmetic were unchanged. Instead, augmented performance in one or both tasks specifically under dual-task conditions indicates that tDCS-induced modulation of cortical excitability enabled participants to better maintain performance in the face of increased cognitive demand.

Improved dual-task performance during tDCS might have arisen from the implementation of alternative cognitive strategies. Task performance under dual-task conditions, for example, is dependent on the priority given to each of the involved tasks (Yogev-Seligmann et al., 2010). Here, we did not provide our participants with specific instructions regarding task prioritization, thus mimicking the majority of real-life situations. Healthy younger and older adults under most circumstances either consciously or unconsciously employ a "posture-first" strategy to ensure the maintenance of balance and minimization of the dangers associated with falling (Yogev-Seligmann et al., 2010). tDCS may have thus reduced the cognitive dual-task costs to standing and walking via reallocation of available cognitive resources between tasks. If this was the case, however, one might predict to observe a "net zero-sum" phenomenon such that an increase in standing or walking performance would come at the expense of a decrease in cognitive task performance (Brem, Fried, Horvath, Robertson, & Pascual-Leone, 2014). This, however, was not the case. Instead, real tDCS reduced the cost of performing mental arithmetic on both standing and walking and, at the same time, reduced (or did not change) the cost induced by standing and walking on mental arithmetic. Therefore, we suggest that tDCS promoted a more efficient recruitment of involved brain networks.

The exact neurophysiological mechanisms that drive dual-task performance are not yet fully understood. The "bottleneck theory" of dual tasking states that, if two tasks share common neural networks, they are processed serially, and as such, processing of one task will be delayed, and performance may be reduced while the other task is being processed (Sigman & Dehaene, 2006; Ruthruff, Pashler, & Klaassen, 2001). Within this context, improvements after real but not sham tDCS might have stemmed from increased processing speed (Redfern, Jennings, Martin, & Furman, 2001; Pashler, 1994). On the other hand, the "capacity-sharing theory" posits that two tasks may be processed concurrently, but performance may be

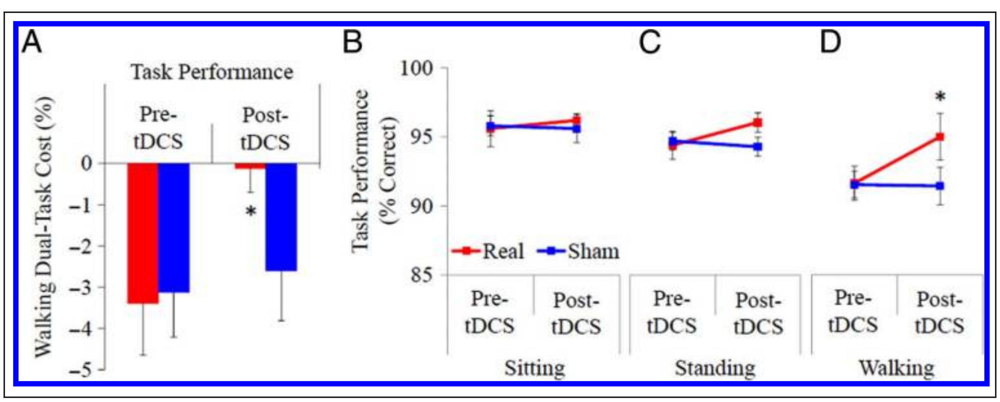

Figure 3. The dual-task costs to serial subtraction task performance before and after tDCS. As compared with sham tDCS, real tDCS reduced the dual-task cost of walking (but not standing) on serial subtraction error rate (A). Further analyses indicated that neither real nor sham tDCS altered task performance in the sitting (B) or standing (C) conditions. Under the walking condition, however, real tDCS improved cognitive task performance (D) and thus reduced the dual-task cost of walking on this outcome. Error bars reflect standard error. Within each panel, an asterisk (*) indicates that the corresponding mean value was significantly different from all other factor means, as determined by Tukey's post hoc testing of significant tDCS condition (real, sham) × Time (pre-tDCS, post-tDCS) interactions within repeated-measures ANOVA models. Means without an asterisk were not different from one another.

diminished by limitations in cognitive resources. Performing two tasks concurrently results in diminished performance in one or both tasks if and when cognitive demand exceeds the total capacity of available cognitive resources (Tombu & Jolicœur, 2003). From this point of view, tDCS may have reduced the costs of dual tasking by increasing the capacity to recruit available cognitive resources or optimizing the allocation of these resources (Filmer, Mattingley, & Dux, 2013; Iuculano & Kadosh, 2013). Future studies that examine other types of cognitive tasks—specifically those that require precisely timed responses to visual or auditory stimuli under sitting, standing, and walking conditions—may delineate the effects of tDCS on processing speed and resource allocation, along with the contributions of these phenomena to dual-task capacity.

As compared with single-task standing or walking, dual tasking effectively increases cognitive demand. One might therefore conceive of the measurable cost of dual tasking while standing or walking as an indicator of one's "cognitive reserve." Cognitive reserve refers to the ability to maintain performance in the face of increased cognitive demand, through the use of alternative cognitive strategies and the differential recruitment of brain networks (Stern, 2002). Cognitive reserve is thought to be a valuable indicator of an individual's ability to maintain behavioral and cognitive function coping with the burden of brain damage, insult, or illness (Valenzuela & Sachdev, 2006). Results of the current study therefore provide proof of concept that the decline in cognitive reserve that is often associated with and attributed to biological aging (Tucker & Stern, 2011) may in fact be minimized by strategies designed to optimize cortical excitability over time. Future studies are therefore warranted to examine the acute and longer-term effects of single and repeated sessions of tDCS in healthy older adults and those suffering from age-related cognitive and/or physical declines.

tDCS was delivered with the anode over the left dorsolateral PFC and cathode over the contralateral supraorbital margin. It is therefore unclear if the observed tDCS-related effects on dual-task costs arose from specific neuronal changes with the left dorsolateral PFC or from changes within other networks of the brain. Moreover, as an inactive sham condition was employed, the observed effects of tDCS may have arisen from general changes in brain excitability. Future studies are therefore needed to examine the comparative effects of active tDCS delivered through different montages. Furthermore, utilizing single and paired-pulse TMS techniques to link tDCS-induced changes in cortical neurophysiology with behavioral changes may elucidate the mechanisms underlying observed enhancement in dual tasking. Finally, the application of neuronavigation techniques is encouraged to optimize the individual effects of tDCS on cortical function and, subsequently, its benefits on dual-task capacity. Nevertheless, this study provides first-of-its-kind evidence that the costs of performing cognitive tasks while standing or walking in older adults can be effectively reduced by modulating prefrontal activity using tDCS.

UNCITED REFERENCE

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Reprint requests should be sent to Brad Manor, 1200 Centre St., Boston, MA 02131, or via e-mail: BradManor@hsl.harvard.edu or Jue Zhang, Academy for Advanced Interdisciplinary Studies, Peking University, Beijing, China, or via e-mail: zhangjue@pku.edu.cn.

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