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Delayed enhancement of multitasking performance: Effects of anodal transcranial direct current stimulation on the prefrontal cortex

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Abstract

Background—The dorsolateral prefrontal cortex (DLPFC) has been proposed to play an important role in neural processes that underlie multitasking performance. However, this claim is underexplored in terms of direct causal evidence.

Objective—The current study aimed to delineate the causal involvement of the DLPFC during multitasking by modulating neural activity with transcranial direct current stimulation (tDCS) prior to engagement in a demanding multitasking paradigm.

Methods—The study is a single-blind, crossover, sham-controlled experiment. Anodal tDCS or sham tDCS was applied over left DLPFC in forty-one healthy young adults (aged 18–35 years)

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immediately before they engaged in a 3-D video game designed to assess multitasking performance. Participants were separated into three subgroups: real-sham (i.e., real tDCS in the first session, followed by sham tDCS in the second session one hour later), sham-real (sham tDCS first session, real tDCS second session), and sham-sham (sham tDCS in both sessions).

Results—The real-sham group showed enhanced multitasking performance and decreased multitasking cost during the second session, compared to first session, suggesting delayed cognitive benefits of tDCS. Interestingly, performance benefits were observed only for multitasking and not on a single-task version of the game. No significant changes were found between the first and second sessions for either the sham-real or the sham-sham groups.

Conclusions—These results suggest a causal role of left prefrontal cortex in facilitating the simultaneous performance of more than one task, or multitasking. Moreover, these findings reveal that anodal tDCS may have delayed benefits that reflect an enhanced rate of learning.

1. Introduction

Attempting to carry out two or more tasks simultaneously is a ubiquitous behavior in modern society. Although multitasking is not beyond human ability, task performance is often significantly compromised when attempting to execute multiple tasks concurrently (Marois & Ivanoff, 2005; Pashler, 1994). Previous studies have suggested that lateral prefrontal cortex is involved in multitasking processes (D'Esposito et al., 1995; Dux, Ivanoff, Asplund, & Marois, 2006; Erickson et al., 2007; Szameitat, Schubert, Muller, & Von Cramon, 2002; Tachibana et al., 2012), with a predominant left-sided prefrontal activation (Bunge, Klingberg, Jacobsen, & Gabrieli, 2000; Collette et al., 2005; Dux et al., 2006). Interestingly, studies have demonstrated that practice and cognitive training can diminish the decline in performance, or multitasking cost, which occurs when engaged in multitasking behavior (Anguera et al., 2013; Bherer et al., 2005; Kramer, Larish, & Strayer, 1995). Importantly, training-based improvements in multitasking performance are thought to arise from cortical activity changes in dorsolateral prefrontal cortex (DLPFC) (Erickson et al., 2007).

A collective view of these findings led us to hypothesize that multitasking performance may be influenced by neuroplastic changes in prefrontal cortical function, and that the DLPFC is a critical node involved in the dynamic changes of this cognitive control system. However, direct causal involvement of DLPFC in multitasking performance is lacking. Two shortcoming of brain lesion studies is that lesions are often non-focal, and compensatory plasticity may have taken place in chronic scenarios. Furthermore, it is also important to address causality in healthy participants. The use of non-invasive neuromodulation to alter function within a brain region has been a useful method to attribute causality to prefrontal regions in a process of interest (Zanto, Rubens, Thangavel, & Gazzaley, 2011). Transcranial direct current stimulation (tDCS) is a non-invasive electrical brain stimulation technique that modulates underlying cortical excitability (Nitsche & Paulus, 2000, 2001) to result in after-

effects on neural processes and behavioral performance (Fertonani, Rosini, Cotelli, Rossini, & Miniussi, 2010; Ohn et al., 2008). These after-effects have been associated with changes of resting membrane potential, alteration of transmembrane protein, and N-methyl-D-aspartic (NMDA) receptor efficiency (Ardolino, Bossi, Barbieri, & Priori, 2005; Liebetanz, Nitsche, Tergau, & Paulus, 2002; Stagg & Nitsche, 2011). Different morphology and axonal orientation also alter the effects of electrical stimulation (Radman, Ramos, Brumberg, & Bikson, 2009). Depending on whether anodal or cathodal stimulation is applied, tDCS increases or decreases motor cortical excitability, respectively (Lang et al., 2005; Nitsche et al., 2008); however, in non-motor cortical areas, this is less consistent such that it is common to observe excitatory effects following anodal tDCS, but rarely are inhibitory effects observed following cathodal tDCS (Jacobson, Koslowsky, & Lavidor, 2012). Studies that applied anodal tDCS over the DLPFC have reported beneficial effects on language performance (Holland et al., 2011), learning processes (Kincses, Antal, Nitsche, Bartfai, & Paulus, 2004), working memory function (Andrews, Hoy, Enticott, Daskalakis, & Fitzgerald, 2011; Fregni et al., 2005), and concurrent discrimination across different modalities, a simplified version of multitasking (Filmer, Mattingley, & Dux, 2013).

The aim of the present study was to clarify the causal role of DLPFC in multitasking by modulating neural activity in this region. To accomplish this, anodal tDCS was applied over each participant's left DLPFC immediately before he or she engaged in a 3-D video game (NeuroRacer) (Anguera et al., 2013) designed to challenge and assess multitasking performance in a dynamic fashion. The experimental group received real tDCS followed by game play, and one hour later received sham tDCS followed by game play. After each stimulation session, performance was evaluated during a single-task condition (perceptual discrimination - sign only (SO) task) and a multitasking condition (perceptual discrimination while visuomotor tracking - sign & drive (SD) task), with the difference between these tasks evidencing a multitasking cost (see NeuroRacer section below). The main comparison of interest was how multitasking performance changed between session one (real tDCS) and session two (sham tDCS). Previous research has revealed that tDCS to the prefrontal cortex may enhance learning (Clark et al., 2012; Kincses et al., 2004), and that by practicing NeuroRacer, participants may learn over time to reduce multitasking cost (Anguera et al., 2013). Although immediate after-effects of tDCS have been observed, our main hypothesis was that tDCS may affect performance on the second assessment as compared to the first, which would indicate that tDCS influenced the rate of learning on the task. To carefully assess immediate versus delayed effects, we included a control group that received sham tDCS first followed by real tDCS after a one-hour intersession interval. Finally, since participants were engaged in the same tasks for two sessions, practice-dependent improvement that is unrelated to tDCS may confound interpretations (Landau, Schumacher, Garavan, Druzgal, & D'Esposito, 2004; Weissman, Woldorff, Hazlett, & Mangun, 2002). Thus, in order to distinguish practice-dependent effects from tDCS-induced effects, we incorporated another control group that received sham tDCS for both sessions.

2. Material and Methods

2.1. Participants

Forty-one healthy adults (mean age: 26.3 y/o; range 18–35 years; 19 males) were recruited in the present study. All participants had normal or correct-to-normal vision, and were free from neurological disorders as well as contra-indications of tDCS. Written informed consent was obtained from each participant according to procedures approved by the University of California at San Francisco, and were compensated for their participation. All participants were randomly assigned into one of the following three groups: sham-sham group (sham tDCS in both sessions), sham-real group (sham tDCS first, followed by real tDCS in the second session one hour later), and real-sham group (real tDCS in the first session, followed by sham tDCS in the second session, conducted one hour later). Data from two participants were excluded as their mean response time in the sign task exceeded 2.5 standard deviations from the mean of all participants.

2.2. Experimental Design

The paradigm is illustrated in Figure 1a. The study was conducted as a single-blind, crossover, sham-controlled trial. All participants were randomly assigned into the real-sham group (N=12), sham-real group (N=13), or sham-sham group (N=14). Each participant engaged in baseline thresholding evaluation to establish the parameters of the component tasks in the multitasking condition, so that each individual played the game at a customized challenge level (see NeuroRacer section below). This was followed by two sessions of tDCS with a 1-hour intersession interval. After each session of tDCS, single-task and multitasking performance were measured using NeuroRacer with tDCS electrode sites carefully checked after every session of tDCS. To assess possible subjective differences between sham and real tDCS, twelve participants (four in each group) were asked to rate their perception of the sensation from the two sessions of tDCS. Thus, participants were given a questionnaire at the end of the experiment that asked them to rate on a scale from 1 (mild) to 10 (severe): headache, neck pain, scale pain, tingling, itching, burning, sleepiness, trouble concentrating, and acute mood change due to tDCS.

2.3. Transcranial Direct Current Stimulation

tDCS was delivered by a battery-driven, constant current stimulator (Chattanooga Ionto, USA) via a pair of saline-soaked sponge electrodes (5.95 cm $\times$ 7.60 cm; 45.22 cm^2). A constant current of 1.0 mA intensity was delivered for 10 min (30-s ramp up and 30-s ramp down). The anode was placed over left DLPFC (centered at electrode F3 of the 10–20 system) and the reference electrode was located over the right supraorbital region (FP2). Using these tDCS parameters, we modeled the magnitude of the total electric field due to stimulation with the NIC software (Neuroelectrics, Spain). Results of the model provided evidence that the tDCS electric field was largest in the left DLPFC and right orbitofronal cortex (Figure 2). The supraorbital region was chosen as the location for reference electrode because there is no evidence that right orbitofrontal cortex is involved in multitasking processes. For sham stimulation, the electrodes were placed at the same positions as real stimulation, but the stimulator was turned off after a 30-s ramp up/ramp down period. Since the onset of tDCS usually generates a tingling or itching sensation over the first minute of

the stimulation, this sham procedure blinded the participants from differentiating real and sham conditions (Nitsche et al., 2003a) and was confirmed by a post-experiment questionnaire (see Results section).

2.4. NeuroRacer

NeuroRacer software was developed using the OpenGL Utility Toolkit (GLUT; http://www.opengl.org/resources/libraries/glut/) as a 3D video game that challenges visual discrimination ability (sign task) alone and in the context of visuomotor tracking (driving task) (Anguera et al., 2013). During the single-task condition (sign only task (SO)) (Fig.1b, left panel), each 3-min experimental run contained 24 targets (green circles) and 48 non-targets (green pentagons and squares; blue and red circles, pentagons, and squares). The signs were randomly presented for 400 ms every 2, 2.5, or 3 seconds. The participants were instructed to ignore the non-target signs and selectively respond to the target sign as fast as possible by pressing a button on a Logitech (Logitech, USA) gamepad controller with their right thumb. A fixation cross that provided performance feedback was present on the screen at all times below the signs (and above the car during the multitasking condition): it turned green for 50 ms when the participant responded to the target sign within the proper amount time after the target showed up, or when a non-target sign was correctly ignored. When either of the aforementioned conditions were not met, it would turn red for 50 ms. During multitasking (sign & driving task (SD)) (Fig.1b, right panel), the participants were told to execute the sign task and concurrently control a car to keep it in a specific area (center of the road, avoiding the yellow and red boundaries) by using the left thumb-stick of the game controller. The road was created by track pieces that included right and left turns, as well as uphill and downhill pieces. These pieces were presented pseudo-randomly for 2, 2.5 or 3 seconds, generating a path that the participant had to guide the car on.

At the beginning of the study, an adaptive thresholding procedure for both driving (twelve 1-min runs) and discrimination (nine 2-min runs) ability was conducted to determine a "drive" and "sign" level that each participant would perform at ~80% accuracy. Having individuals engage in the component tasks at their own difficulty level provided a means to normalize challenge so that the assessment of multitasking skills was not confounded by group and individual differences in abilities. During driving thresholding, the difficulty of the driving task changed depending on the percentage of time the car stayed on the road. The adaptive staircase algorithm adjusted the speed of the road on each subsequent 3-min run based on participants' performance. A driving accuracy greater than 82.5% led to a faster road speed, and a driving accuracy lower than 77.5% resulted in a slower road speed. For perceptual discrimination (sign) thresholding, a proportion of correct responses to all presented signs greater than 80% led to a shorter time window allowed for responses to targets on a subsequent run, and vice versa for performance less than 80% (for more details, please see Supplementary Figure 1 of Anguera et al., 2013). Correct responses are determined by accuracy, as well as whether the response occurs within the allotted time window.

Following each tDCS session, participants engaged in three different 3-min tasks: single-task (Sign Only, SO), multitasking (Sign and Driving, SD), and a distraction-task (Sign with Road, SWR). The order of the three tasks was randomly assigned. In the distraction task,

participants were told to respond to the signs and ignore the auto-driving car. Each task was performed three times per session with the order of tasks counterbalanced across participants. Performance feedback was given at the end of each run to the participants as the percentage of time spent on the road and the proportion correct to all signs presented. Prior to each run of the task, participants were informed of which task would be performed next.

2.5. Data analysis

To investigate effects of DLPFC neural modulation on multitasking performance, we evaluated perceptual discrimination performance following each tDCS session using a metric of discrimination performance (d') (Macmillan & Creelman, 2005), which was estimated for each participant by comparing hit (correct responses to target signs) rates and false alarm (responses to non-targets) rates and calculated as d' = Z(hits) – Z(false alarms). A cost index was also used to measure multitasking performance by calculating the percentage change in d' from single-tasking (SO task) to multitasking (SD task) (multitasking cost index = (d' for SD - d' for SO) / (d' for SO)). Thus, a smaller multitasking cost index (i.e., a less negative % cost) indicates less interference when engaging in the two tasks concurrently (i.e., better multitasking performance).

The difference in baseline (session 1) performance (multitasking cost and discrimination performance (d')) across the three groups (sham-sham, sham-real, real sham) was examined using a one-way ANOVA. Multitasking cost differences were assessed by a two-way repeated measures ANOVA with group (sham-sham, sham-real, real-sham) and session (session 1, session 2) as factors. d' itself was analyzed using a three-way repeated measures analysis of variance (ANOVA) with task (SO, SWR, SD) and session (session 1, session 2) as within-subject factors and group (sham-sham, sham-real, real-sham) as a between-subject factor. The Greenhouse-Geisser correction was applied when appropriate, with paired t-tests carried out for direct comparisons. The perception of sensation (scaled from 1 to 10) for each tDCS session was analyzed with paired t-tests to assess participant blindness to stimulation type (real or sham). All the measured data was presented as the mean ± standard error of mean (SEM). Statistical significance threshold was set as $p<0.05$.

3. Results

Confirming that the sham was an appropriate placebo manipulation, there were no statistical differences in the perception of stimulation between the sham tDCS and real tDCS sessions (scalp pain, $t_{11}=1.00$, $p=0.33$; tingling, $t_{11}=0.51$, $p=0.61$; itching, $t_{11}=1.10$, $p=0.29$; burning sensation, $t_{11}=0.41$, $p=0.68$).

3.1. Multitasking cost

To explore the effects of prefrontal cortex neural modulation on multitasking performance, we first assessed whether tDCS altered the multitasking cost index using a two-way ANOVA. The two-way ANOVA showed no main effects (group effect: $F_{2,36}=0.46$, $p=0.62$; session effect: $F_{1,36}=0.75$, $p=0.39$), but a two-way interaction between session and group was found ($F_{2,36}=4.15$, $p<0.05$). As predicted, post-hoc tests demonstrated a lower

multitasking cost in the second session compared to the first session *only* in the group who received real tDCS stimulation first (real-sham: t_{11}=3.66, *p*<0.05; sham-real: t_{12}=−1.10, *p*=0.29; sham-sham: t_{13}=0.28, *p*=0.78) (Table 1; Fig.3a). There was no significant difference in multitasking cost among the three groups at baseline ($F_{2,36}$=0.20, *p*=0.82). Figure 3b depicts individual data of multitasking cost changes from session 1 to session 2 for each group. In the real-sham group, ten out of twelve participants showed diminished multitasking cost from session 1 to session 2. Again, no consistent changes in multitasking cost were found across participants in both sham-real (six out of thirteen) and sham-sham (seven out of fourteen) groups. Data from one participant in the sham-real group exceeded 2.5 standard deviations from the mean of this group. Nevertheless, the statistical results for multitasking cost remained the same after discarding the data from this participant.

To further compare the results of the three groups, effect sizes for multitasking cost were calculated based on the difference in performance between the two sessions for each group using Cohen's d (Cohen, 1992). Absolute effect size values ranged from 0.2 to 0.5 were considered to be small, those between 0.5 and 0.8 were considered to be moderate, and those over 0.8 were considered to be large (Cohen, 1992). Fig.4 illustrates the effect sizes for multitasking cost from each group. The multitasking cost effect sizes were small in sham-sham (effect size: 0.10) and sham-real (effect size: 0.27) groups, whereas the effect size in real-sham group was large (effect size: 0.82). Finally, t-tests were conducted to compare the change in multitasking cost from session 1 to session 2 between the three groups. The multitasking cost difference between the two sessions was substantially greater for the real-sham group (significant 20% reduction in cost) compared to sham-sham (non-significant 2% decrease in cost) (t_{24}=−2.15, *p*<0.05) or sham-real (non-significant 10% increase on cost) (t_{23}=2.70, *p*<0.05) group, supporting the finding that tDCS significantly reduced multitasking cost in the real-sham group in a delayed fashion.

3.2. Discrimination performance (d')

To determine whether tDCS cost effects were selective for the multitasking condition (SD), a three-way ANOVA was conducted for d' results. A significant main effect of task ($F_{2,27}$=82.81, *p*<0.001) and a marginally significant three-way interaction between task × session × group were observed ($F_{4,72}$=2.36, *p*=0.06). Two-way ANOVAs were conducted for each task (SD, SWR, and SO). A significant session × group two-way interaction was observed for the SD task ($F_{2,36}$=3.46, *p*<0.05), and not the SWR task ($F_{2,36}$=1.15, *p*=0.33) or SO task ($F_{2,36}$=0.14, *p*=0.86). A significant session × group two-way interaction was observed for the SD task, implying that the three groups showed different levels of changes in d' from first to second session. Taken these together, we conjecture that the effects of tDCS were selective for multitasking. One-way ANOVA revealed a comparable baseline discrimination performance (d') among the three groups in SO task ($F_{2,36}$=0.47, *p*=0.62), SWR task ($F_{2,36}$=0.32, *p*=0.72), and SD task ($F_{2,36}$=0.10, *p*=0.90). Post-hoc analyses of the SD task data indicated that the real-sham group showed a higher d' during the second session compared to the first session (t_{11}=2.46, *p*<0.05; Table 1; Fig.5a), while no significant differences in d' were found between the first and the second sessions for sham-real (t_{12}=0.81, *p*=0.42) and sham-sham (t_{13}=0.28, *p*=0.78) groups. These findings inform the multitasking cost results by revealing that it was driven by tDCS actually improving

multitasking performance in the second assessment for the real-sham group and further confirmed the lack of tDCS effects on both sham-real and sham-sham groups. Post-hoc analyses of SWR and SO tasks data indicated that tDCS effects induced no significant differences between first and second sessions for any of the groups, consistent with the lack of a significant interaction (Table 1; Fig. 5b and 5c). Effect sizes for d' were also calculated based on the difference in performance between the two sessions for each group. Again, only the real-sham group showed moderate effect size (0.56) for d' in multitasking condition (Table 1). These results suggest that tDCS induced a selective, delayed beneficial effect on multitasking performance, as evidenced by a positive impact of tDCS on subsequent discrimination d' only: i) in the multitasking condition, and ii) in the second session relative to the first only for the real-sham group.

To directly compare tDCS effects between the SD and SO tasks in the real-sham group, d' differences between session 1 and session 2 were compared. A paired t-test revealed that the d' difference between the two sessions in SD task was significantly greater than for the SO task (t_{11}=3.47, *p*<0.05; Fig.5d). Further between group comparisons also showed that the d' difference between the two sessions in SD task was substantially larger for the real-sham group compared to sham-sham (t_{24}=2.17, *p*<0.05) or sham-real (t_{23}=−2.31, *p*<0.05) group. Thus, tDCS effects on SD were greater than for SO, supporting the interpretation that tDCS selectively impacted multitasking performance. Moreover, this tDCS effect was greater for real-sham group than for sham-sham and sham-real groups.

To further examine whether the improved visual discrimination performance in real-sham group was achieved at the cost of the visuomotor tracking task, we further analyzed the visuomotor tracking (driving) performance. Data from one of the participants in real-sham group was not included in this analysis because of technical issues. The percentage of time the car stayed on the road in the time window from 500 ms before to 1000 ms after the target signs (green circles) were presented was calculated. A two-way repeated measures ANOVA with group (sham-sham, sham-real, real-sham) and session (session 1, session 2) as factors was performed. The two-way ANOVA showed no main effects (group effect: $F_{2,35}$=0.43, p=0.65; session effect: $F_{1,35}$=1.00, p=0.32). Session × group interaction also failed to reach the significant level ($F_{2,35}$=0.79, p=0.46). These results suggested that improvement of the visual discrimination task in real-sham group was not caused by the different prioritizations of the two tasks among the groups.

4. Discussion

In the present study, we aimed to explore the causal role of DLPFC function on multitasking performance via perturbation of this region with transcranial neuromodulation. To accomplish this, we assessed the effect of anodal tDCS over left DLPFC on subsequent perceptual discrimination performance with and without a concurrent secondary task in two sessions that were performed one hour apart. Results revealed that anodal tDCS applied for 10 min immediately before task engagement improved multitasking performance approximately one hour later. Specifically, we showed 20% reduction of d' multitasking cost in the second session compared to the first session that was driven by increased d' on the perceptual discrimination task while concurrently engaged in a visuomotor tracking task.

This across-session improvement is unlikely to stem from practice effects, as the performance in a sham-sham group did not change across sessions. Also, the effect could not be accounted for by a negative influence of real tDCS on the first session of assessment, as the sham-real group did not show performance declines after real tDCS compared to sham. This absence of a change in the sham-real group also confirmed that the impact of tDCS on multitasking performance occurred only as a delayed effect. Moreover, these effects were selective for the multitasking condition, as they did not occur for the perceptual discrimination task when it was engaged in isolation (i.e., single-task) or under distraction (i.e., distraction-task). Together, these results provide evidence that left DLPFC plays a causal role in multitasking and further supports tDCS as a potentially promising method to enhance multitasking performance.

The DLPFC has been reported to be involved in several domains of cognitive control abilities that support multitasking behavior, such as attention shifting (Kondo, Osaka, & Osaka, 2004; Ravizza & Carter, 2008), sustained attention (Ortuno et al., 2002), task switching (Hyafil, Summerfield, & Koechlin, 2009; Yoshida, Funakoshi, & Ishii, 2010), selective attention (Hadland, Rushworth, Passingham, Jahanshahi, & Rothwell, 2001; Vanderhasselt, De Raedt, Baeken, Leyman, & D'Haenen, 2006), working memory (Gazzaley, Rissman, & D'Esposito, 2004) and inhibitory control (Hoppenbrouwers et al., 2013). Here we provide supporting evidence that the left DLPFC is causally involved in higher-order cognitive control required during multitasking, as has been suggested by previous correlational methodology (D'Esposito et al., 1995; Erickson et al., 2007; Goldberg et al., 1998; Kondo et al., 2004; Szameitat et al., 2002; Tachibana et al., 2012). During multitasking, active maintenance of multiple streams of information is required (Kramer & Strayer, 1988) and the DLPFC has been proposed to be a critical hub for managing limited attentional resources (Low, Leaver, Kramer, Fabiani, & Gratton, 2009). The current results, demonstrate not only the utility of the left DLPFC in multitasking, but that neural modulation techniques may selectively enhance multitasking performance abilities.

According to previous studies, tDCS modulates resting membrane potential (Liebetanz et al., 2002; Purpura & McMurtry, 1965), and anodal current increases cortical excitability at the site of stimulation (Nitsche et al., 2003b; Nitsche & Paulus, 2001). Thus, multitasking performance improvements (20% reduction of multitasking cost) observed in the present study may be considered the consequences of enhanced cortical excitability in the left DLPFC. However, it remains unclear exactly what cognitive process(es) may have benefitted to enhance multitasking performance. To successfully perform NeuroRacer, there is the need to engage selective attention resources for the perceptual discrimination task, in addition to the array of cognitive control skills involved in the act of multitasking. Interestingly, although it has been shown that DLPFC is engaged during selective attention (Hadland et al., 2001; Vanderhasselt et al., 2006), tDCS-induced improvements in discrimination performance were only observed for the multitasking condition and not for the single-task discrimination condition or distraction-task. Driving performance also remained the same and not affected by tDCS from the first to second session. These results suggested that improvement of the visual discrimination task in real-sham group was not caused by the different prioritizations of the two tasks or achieved at the cost of the visuomotor tracking task. Alternatively, given the role of the DLPFC in attention shifting

(Kondo et al., 2004; Ravizza & Carter, 2008), it is equally possible that tDCS increased the ability to switch attentional focus between the visuomotor tracking and perceptual discrimination tasks.

It may be argued that the observed tDCS effects only on multitasking performance is the result of the discrimination task being more difficult when multitasking than when performed in isolation (Low et al., 2009; Szameitat et al., 2002). However, note that participants were thresholded prior to the task to ensure that single-task performance was not at ceiling, and based on previous research, we know that single-task discrimination performance is capable of improving from baseline levels with training (Anguera et al., 2013). Future studies that manipulate single-task difficulty levels will help assess a specific role of DLPFC in isolated cognitive control processes.

Interestingly, the improvement of multitasking performance was only observed in real-sham participants, as revealed by improved discrimination only when multitasking in the second tDCS session compared to the first session. The results from the real-sham group and sham-real group confirmed that tDCS-based enhancement of multitasking ability occurred off-line and as a delayed effect on performance at a subsequent session, and not as an acute effect on the session immediately following stimulation. The observed off-line, delayed tDCS effect is most likely related to learning processes altered by tDCS. Residual tDCS after-effects have been previously reported, such that anodal tDCS to the left DLPFC enhanced verbal working memory, and this benefit was maintained 30 min after the completion of tDCS application (Ohn et al., 2008). It was also reported that motor cortex excitability can be changed up to 60 min or longer after 9–13 min of 1.0 mA tDCS application (Nitsche et al., 2003b; Nitsche & Paulus, 2001). However, the duration of tDCS after-effects may differ between motor cortex and prefrontal areas (Andrews et al., 2011; Fregni et al., 2005). Since the inter-session interval of the present study was 1 hour, the after-effect of stimulation seems to have persisted as least 1 hour. Also, it is important to consider that beneficial effects of tDCS on multitasking performance may have needed a certain amount of task engagement in order to manifest the enhancements. The sham-real group was included to determine if the tDCS immediately prior to the second session was sufficient to result in an improvement of performance in that session relative to the first. This group also showed no significant difference in performance between the first and second session. This data does not offer an explanation as to why there was no prominent practice effect; however, in the context of our previous NeuroRacer training work (Anguera et al., 2013) where training effects were observed after 12 hours of training (20 - 3min multitasking runs each day of training). The possibility exists that the number of runs completed was not enough to generate a statistically meaningful learning effect without the first session following tDCS.

The delayed effects in the current study suggest that the impact of tDCS was to enhance the rate of learning to multitask. In support of this, McKinley, McIntire, Bridges, Goodyear, and Weisend (2013) demonstrated that tDCS to the prefrontal cortex during visual search training did not improve subsequent change detection performance; however, performance improved following a second training session where sham tDCS was applied. These results are similar to our current findings and suggest an experience-dependent tDCS effect. Furthermore, Reis et al. (2009) conducted a 5-consecutive day training study and showed

that anodal tDCS enhanced motor skill acquisition, both on within-day and between-day assessments. Importantly, the performance differences between anodal and sham conditions were primarily driven by between-day effects, suggesting that tDCS induces motor-learning consolidation (Reis et al., 2009). Related to this, applying anodal tDCS to the prefrontal cortex can facilitate declarative (Marshall, Molle, Hallschmid, & Born, 2004) and long-term (Javadi & Cheng, 2013) memory consolidation. Thus, it is possible that our observed delayed tDCS effects reflect an enhancement of multitasking learning through rapid consolidation processes. Despite the results demonstrating that anodal tDCS improved multitasking performance, the anode-excitatory cathode-inhibitory dichotomy of tDCS effects is less consistent in non-motor area (Jacobson, Koslowsky, & Lavidor, 2012), therefore, the polarity-specificity of tDCS effects on cognitive function needs further investigation.

Interestingly, we have previously demonstrated that training over the course of a month improves multitasking abilities (Anguera et al., 2013). With a total of 12 hours training on an adaptive version of NeuroRacer over one month by older adults, we found a 48% reduction of multitasking cost from pre- to post-training assessment. In the present study, a 20% decrease in multitasking cost was observed after 10 min of tDCS administration. Although the studied population (older vs. younger adults) and the methods used to induce neuroplastic changes (cognitive training vs. tDCS) are different in the two studies, the observed tDCS effects may operate on similar mechanisms as those affected by cognitive training. This will be the focus of future investigations.

In a recent study, Filmer, Mattingley, and Dux (2013) assessed concurrent multimodal discrimination performance before, immediately after, and 20 min after anodal, cathodal, or sham stimulation to the left DLPFC. Their results showed that response times on this divided attention task (categorizing both audio and visual stimuli) improved immediately after 9 min of cathodal stimulation, but not by either anodal or sham stimulation. It may seem as if the present findings are in conflict with those from this report, since Filmer et al. (2013) reported cathodal tDCS to the left DLPFC immediately enhances a type of multitasking performance, whereas our results show that anodal tDCS over the left DLPFC enhances multitasking performance an hour after stimulation. These differences are not likely attributable to tDCS methodology, as stimulation in both experiments were conducted offline following 1 mA for a comparable duration of time (9 min vs 10 min) and with the same electrode placement (F3 (left DLPFC) and FP2 (supraorbital)). Since the effects of tDCS on behavioral performance have been shown to be task dependent (Antal, Kincses, Nitsche, Bartfai, & Paulus, 2004; Boggio et al., 2006; Fregni et al., 2005; Kincses et al., 2004), the different results might have been due to the very different cognitive paradigms that were employed. In the Filmer study, participants were instructed to discriminate and select the appropriate (finger) response to auditory and visual stimuli presented simultaneously, which places large processing demands on mapping sensory information onto motor responses (Filmer et al., 2013). Our multitasking paradigm required simultaneous visual discrimination and visuomotor tracking without an impact of motor mapping influencing discrimination processing. Thus, the precise functional mechanism underlying performance on the two paradigms might be a factor.

Filmer and colleagues (2013) also utilized response times to evidence changes in performance for single versus multitasking. Slowed response times when multitasking are suggested to reflect delays in distinct aspects of cognitive processing (e.g., response selection, short term memory encoding, or stimuli identification) related to completing the second task while processes engaged for the first task are still online (cf. psychological refractory period, PRP) (Dux & Marois, 2009; Pashler, 1994; Shapiro, Raymond, & Arnell, 1997). Our use of a continuous visuomotor tracking task that engaged perception, visual-spatial deployment, and response-selection (see also (Rushworth, Hadland, Gaffan, & Passingham, 2003)) concurrently with a perceptual discrimination task is more reflective of the complex acts often involved in real-world human multitasking, and also prevents response time biases that result when similar task structures are engaged. Another possible reason for the different findings of these two studies may lie with task difficulty. Participants in Filmer et al.'s (2013) study performed around 95%, whereas in our study, each participant was thresholded prior to the main experiment in order to ensure single-task performance was around 80%. Thus, anodal tDCS in our study may have enabled participants to learn how to improve multitasking abilities (delayed effects), whereas cathodal tDCS in Filmer et al.'s (2013) study may have served to prevent mind wandering during a relatively simple task (immediate effects), a possibility that warrants further investigation.

A potential limitation of the present study is the single-blinded approach. As our tDCS system only allowed turning off the simulator manually, the experimenter was not blinded. The single-blinded design may limit the conclusions drawn from the present study. Future research should assess these effects in double-blinded tDCS experiments. Another issue should be taken into account with respect to the interpretation of the present results: as the sponge electrodes were relatively large (45.22 cm^2), the neuromodulation effects on functionally connected areas or adjacent cortical regions other than DLPFC cannot be fully ruled out. Yet, the size of the tDCS electrodes are certainly large enough to encompass the majority of the DLPFC and the effects are expected to be most pronounced in this region, as previously suggested when using similar methods (Dockery, Hueckel-Weng, Birbaumer, & Plewnia, 2009; Fregni et al., 2005; Ohn et al., 2008).

5. Conclusions

In summary, the present results reflect a causal role of anodal stimulation over left DLPFC in the performance of multiple tasks at the same time. tDCS effect is selective for the multitasking condition. The study provides evidence that direct augmentation of cortical excitability over left DLPFC enhances multitasking by tDCS-induced delayed effects one hour after stimulation. The improvement of the visual discrimination task in real-sham group was not caused by the different prioritizations of the two tasks among the groups. Further functional neuroimaging studies are warranted to clarify the neural mechanisms underlying tDCS-induced multitasking performance enhancement.

Acknowledgements

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(a)

(b)
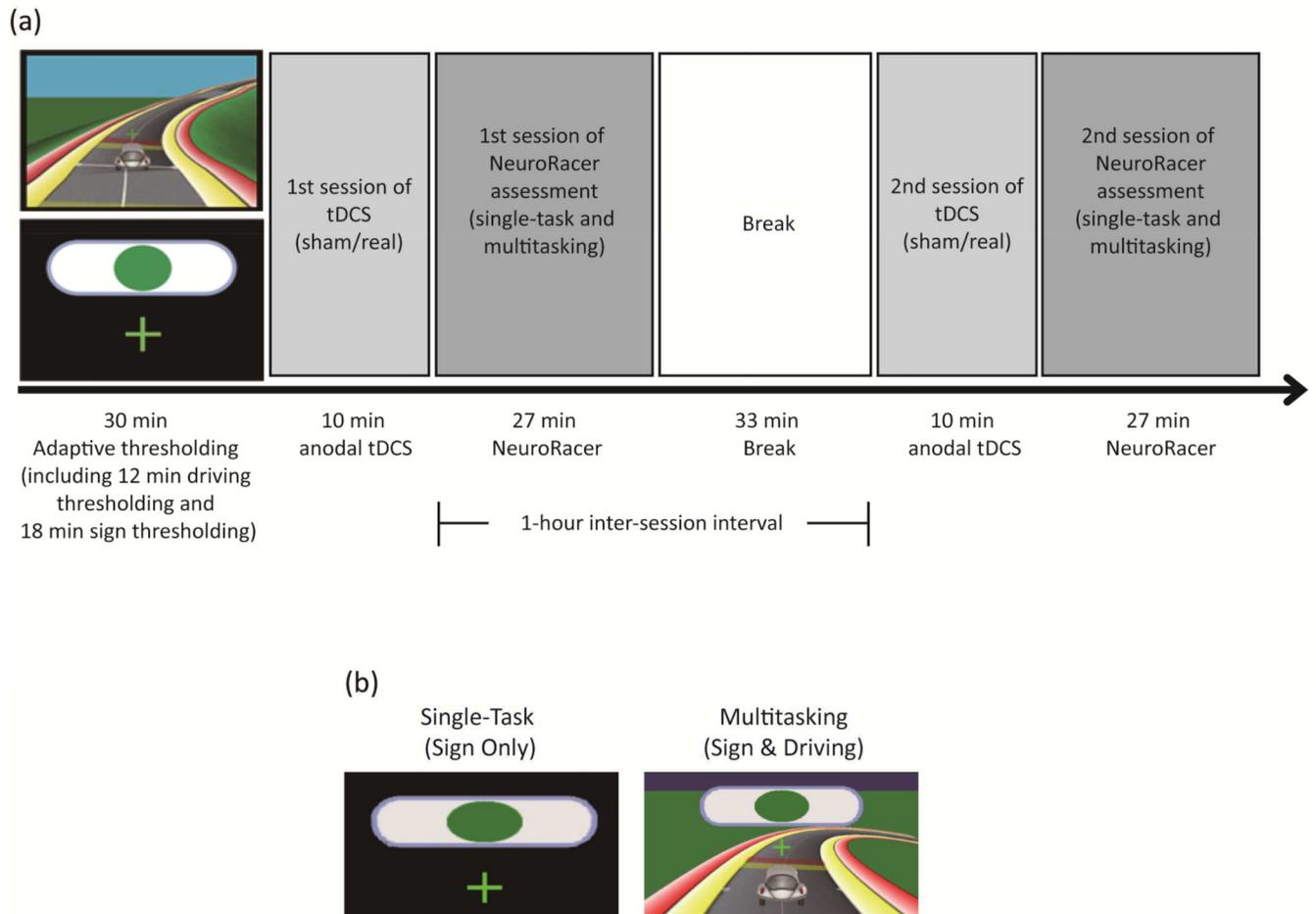
Figure 1. Experimental design
(a) Following thresholding evaluation (twelve runs for driving thresholding and nine runs for sign thresholding), participants took part in two sessions of 10-min tDCS and 27-min NeuroRacer assessment of single-task and multitasking. Time interval between the two sessions was 1 hour. (b) NeuroRacer assessment for single-task (sign only) and multitasking (sign and driving). During sign only task, the participants only had to respond to the target sign (green circles) as fast as possible and ignore non-targets. In sign and driving task, the participants were instructed to control a car to keep it at the center of the road and simultaneously respond to the target sign as well as ignore non-targets.
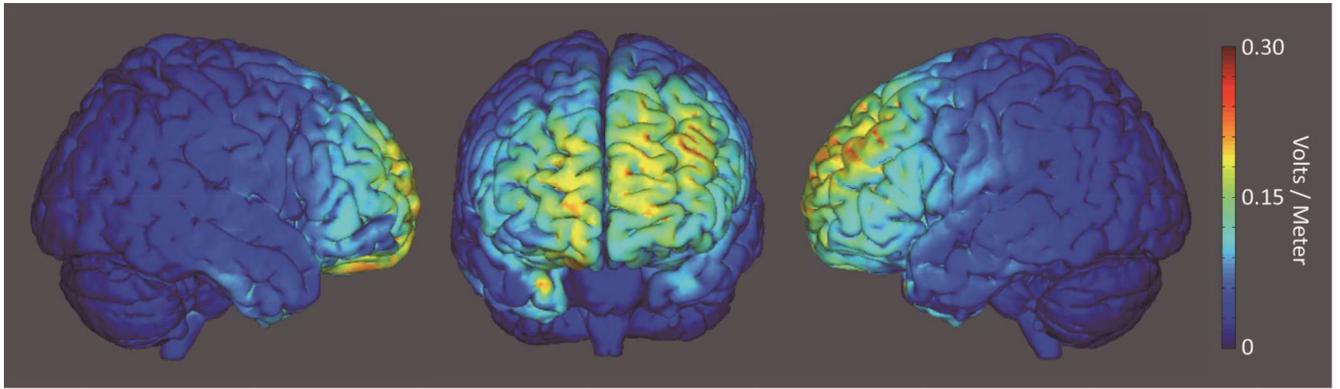
Figure 2.
Model of tDCS. Red-yellow colors indicate increased magnitude of the total electric field due to tDCS. Left panel displays right hemisphere, center panel shows frontal regions, and the right panel depicts the left hemisphere and highlights stimulation within the left DLPFC.
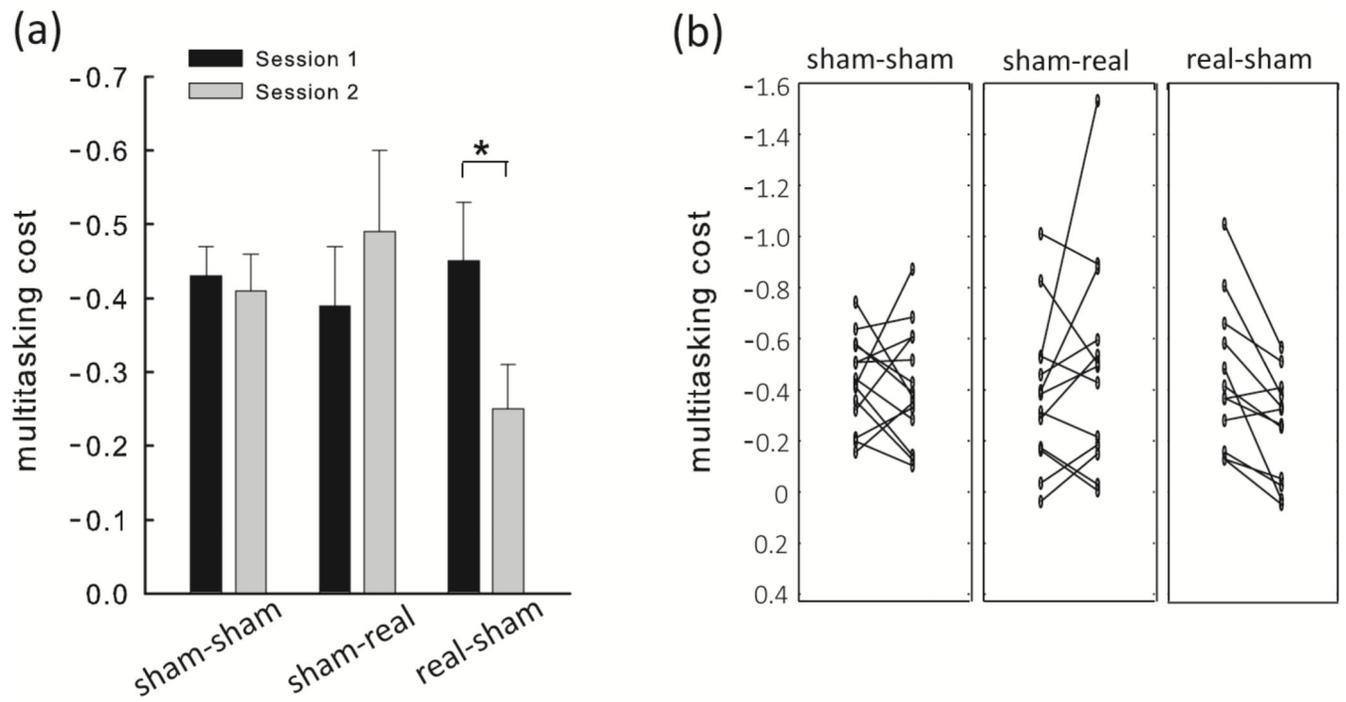
Figure 3. Multitasking cost results
(a) Multitasking cost was significantly decreased in second session than that in the first session for real-sham group (p=0.004). Error bars represent SEM. (b) Individual data of multitasking cost changes from session 1 to session 2 for each group. Ten out of twelve subjects in real-sham group showed reduced multitasking cost from session 1 to session 2.
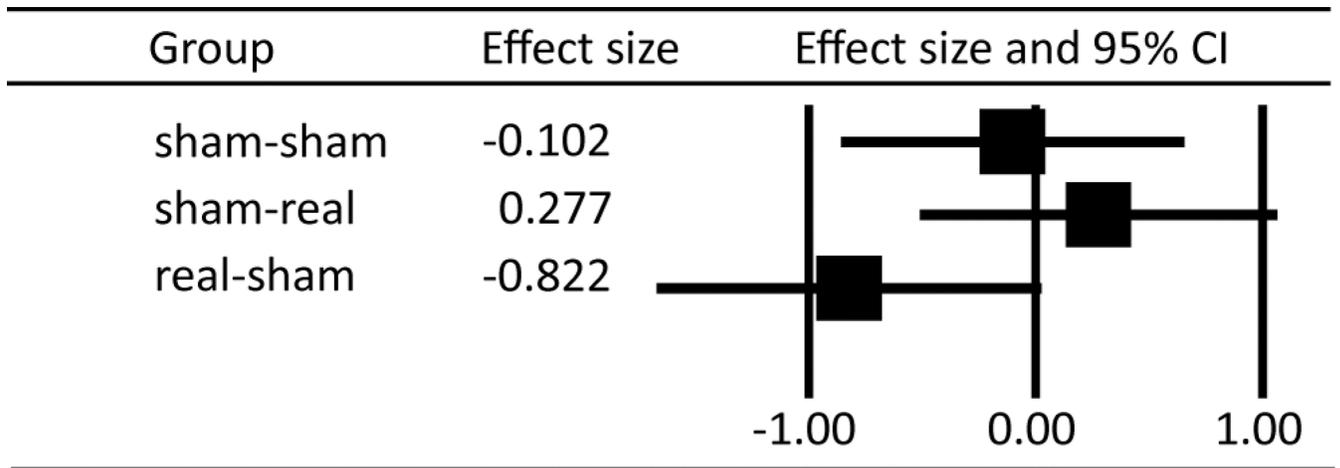
Figure 4. Effect sizes of multitasking cost
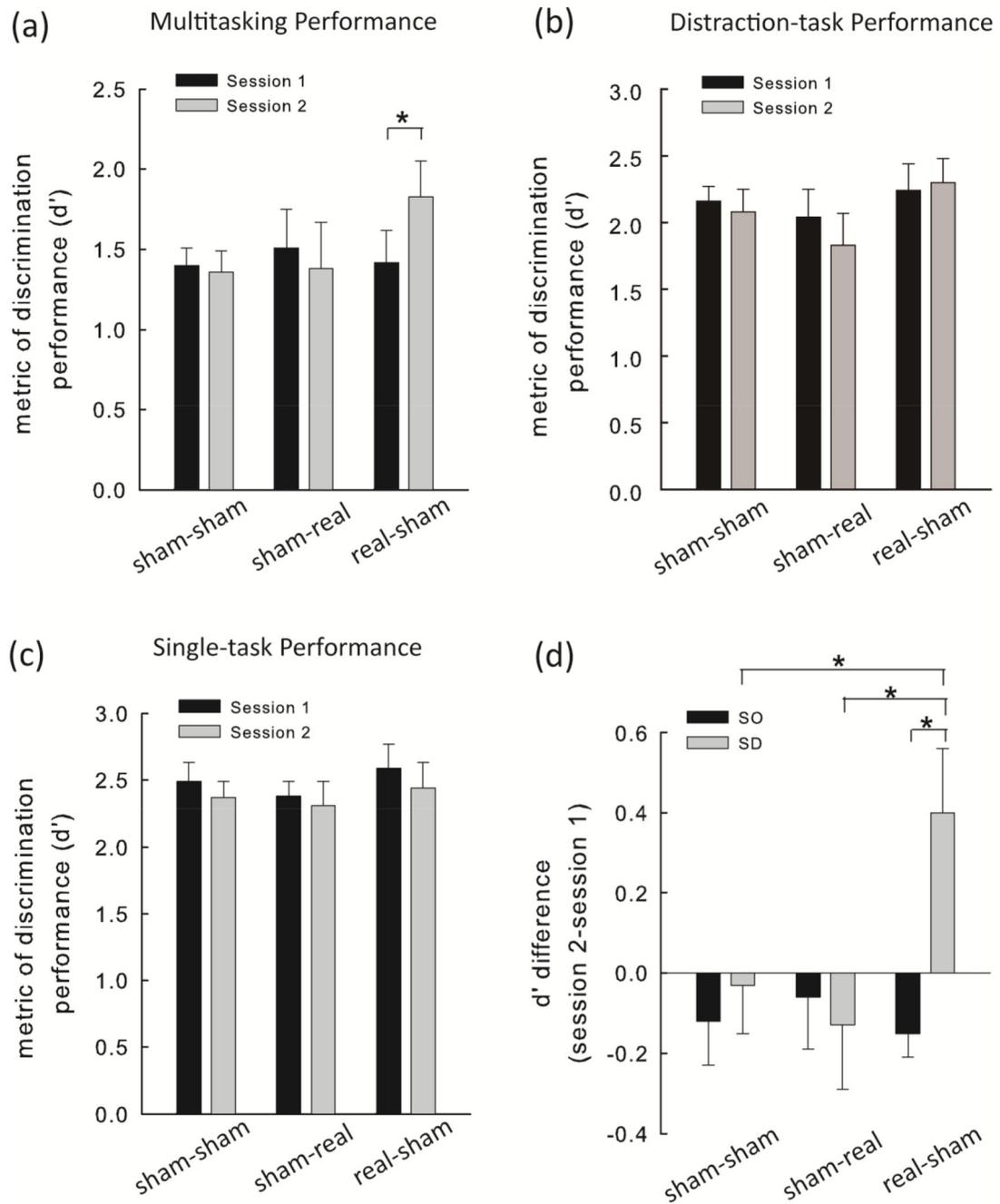
Figure 5. Behavioral performance during multitasking and single-task

(a) Multitasking (SD) d' in real-sham group was significantly increased in the second assessment compared to the first assessment (p=0.03). (b) No statistical differences were found in distraction-task (SWR) performance between the two sessions. (c) No statistical differences were observed in single-task (SO) performance between the two sessions. (d) The d' differences between the two sessions was substantially larger in SD task compared to SO task (p=0.005) in real-sham group. d' difference between the two sessions in SD task was substantially larger in real-sham group when compared to sham-sham (p=0.04) or real-

sham (p=0.01) group. SO, sign only; SD, sign and driving; SWR, sign with road. Error bars represent SEM.

Table 1

Multitasking performance results

	Group	Session 1	Session 2	Effect Size
d'for SD	sham-sham	1.40 (0.11)	1.36 (0.13)	−0.08
	sham-real	1.51 (0.24)	1.38 (0.29)	−0.13
	real-sham	1.42 (0.20)	1.83 (0.22)*	0.56
d' for SWR	sham-sham	2.16 (0.11)	2.08 (0.17)	−0.15
	sham-real	2.04 (0.21)	1.83 (0.24)	−0.26
	real-sham	2.24 (0.20)	2.30 (0.18)	0.09
d' for SO	sham-sham	2.49 (0.14)	2.37 (0.12)	−0.24
	sham-real	2.38 (0.11)	2.31 (0.18)	−0.13
	real-sham	2.59 (0.18)	2.44 (0.19)	−0.23
multitasking cost	sham-sham	−0.43 (0.04)	−0.41 (0.05)	−0.10
	sham-real	−0.37 (0.07)	−0.40 (0.07)	0.27
	real-sham	−0.45 (0.08)	−0.25 (0.06)*	−0.82

d', metric of discrimination performance; SD, sign and driving; SWR, sign with road; SO, sign only.

*p<0.05 for the comparison between session 1 and session 2.