

Effect of combined yoga and transcranial direct current stimulation intervention on working memory and mindfulness

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Transcranial direct stimulation, a non-invasive neurostimulation technique for modulating cortical excitability, and yoga have both respectively been shown to positively affect cognition. While preliminary research has shown that combined transcranial direct stimulation and meditation may have synergistic effects on mood and cognition, this was the first study to explore the combination of transcranial direct stimulation and yoga. Twenty-two healthy volunteers with a regular yoga practice were randomized to receive either active transcranial direct stimulation (anodal left, cathodal right dorsolateral prefrontal cortex) followed by yoga intervention or sham transcranial direct stimulation followed by yoga intervention a double-blind, cross-over design over two separate intervention days. Outcome measures included working memory performance, measured with the n-back task and mindfulness state, measured with the Toronto Mindfulness Scale, and were conducted offline, with pre-post assessments. Twenty participants completed both days of the intervention. Active transcranial direct stimulation did not have a significant effect on working memory or levels of mindfulness. There was a significant placebo effect, with better performance on day 1 of the intervention, irrespective of whether participants received active or sham transcranial direct stimulation. There was no significant difference between active versus sham transcranial direct stimulation concerning working memory performance and mindfulness, which may be accounted by the small sample size, the transient nature of the intervention, the fact that yoga and transcranial direct stimulation concerning were not conducted simultaneously, and the specific site of stimulation.

Keywords

Transcranial direct-current stimulation; Yoga; Mindfulness; Working memory; Cognition

1. Introduction

Over the last several decades, there has been a growing interest in the therapeutic benefits of meditation and yoga. While yoga involves elements of meditation, it differs from conventional meditation Cognition its focus on postures and movement. Yoga has been demonstrated to benefit car-

diorespiratory health, metabolic conditions, musculoskeletal conditions and mental health [1]. The beneficial effects of yoga have been linked to physiological and neurocognitive mechanisms underlying the observed effects. For example, electrophysiological studies have demonstrated increased activation of theta and alpha bands, reflecting enhanced sustained attention [2]. Yoga based interventions have been shown to lead to significant increases in gray matter volume and enhanced activation of the amygdala and frontal cortex [1].

Transcranial direct current stimulation (tDCS) is a non-invasive, non-convulsive neurostimulation technique for studying and modulating neural excitability [3–5]. TDCS can be used with active or sham stimulation protocols, enabling efficient blinding in research studies [6]. TDCS can significantly affect behavior, cognitive performance, and mood, depending on the site, polarity, and timing of stimulation [7–12].

In tDCS, a weak tonic current is applied between two or more electrodes placed on the scalp. Its effects on cortical excitability are polarity-specific, with anodal stimulation increasing cortical excitability and cathodal tDCS decreasing it at the macroscopic level with conventional protocols [13]. The primary effects accomplished immediately during short stimulation are caused by subthreshold de- or hyperpolarization of the neuronal resting membrane potential [14]. Prolonged stimulation durations can result in long-lasting after-effects, resembling neuroplastic changes. While the immediate primary effects involve voltage-dependent sodium and calcium channels, neuroplastic after-effects depend on glutamatergic NMDA and AMPA receptors, and downregulation of GABA activity [3, 4, 15, 16].

tDCS has been shown to have a positive effect on working memory, with the majority of studies stimulating prefrontal regions, with the anode targeting the left dorsolateral prefrontal cortex (DLPFC) [17–19]. Previous neuroimag-

ing research has specifically identified the DLPFC to play a prominent role in working memory and mindfulness [20–25]. While there has been little research linking tDCS alone with immediate improvements in mindfulness, encouraging results have been reported for the impact of combined tDCS-mindfulness training approaches on mindfulness ratings [26, 27]. A recent study investigated the impact of a two-week mindfulness-based training with concurrent tDCS on working memory and attentional resource allocation. tDCS involved anodal stimulation over the right inferior frontal gyrus, with the cathode positioned at the contralateral upper arm. The combined intervention was associated with improved verbal working memory performance [28]. In [29], the impact of a combination of 20 minutes of guided meditation and simultaneous tDCS was examined. The anode was placed over the right inferior frontal gyrus (F8), and the cathode was placed over the left supraorbital region.

In comparison with sham stimulation, active tDCS resulted in significantly enhanced self-reported levels of mindfulness, though no association was found with mood [29]. Interestingly, in [30], a combination of meditation with 20-minute tDCS, and the anode placed over the primary motor cortex (cathode placed contralaterally supraorbital), the intervention was found to help alleviate pain. Beyond these encouraging results, a recent study [31], exploring the effect of 30 minutes of tDCS with the anode placed over the left DLPFC, and the cathode over the contralateral upper arm, concurrently with loving-kindness meditation, found no difference between active vs. sham tDCS on emotional processing. While the studies mentioned above involved specific meditation interventions, there have been no studies to specifically explore the impact of yoga coupled with tDCS. In the present exploratory study, we investigated the effect of a single session of tDCS coupled with a yoga intervention on working memory and mindfulness.

2. Methods

2.1 Participants

Participants were recruited via flyers posted at the University of British Columbia hospitals and local yoga studios/wellness shops, online advertisements, and email blasts delivered via the university hospital listserv and local yoga studio email lists. In total, Thirty-five participants were screened, and 13 of these did not meet the study eligibility criteria. Two individuals dropped out after the first visit from the 22 healthy volunteers (Mean age = 29.05 ± 4.56) randomized, and two individuals dropped out after the first visit. Study inclusion criteria were yoga practitioners with two or more years of regular yoga practice of at least two sessions per week, ability to provide voluntary consent, between the ages of 18 and 35 years and successful pass of the tDCS safety screening. Exclusion criteria were (1) women using hormonal contraception, (2) pregnancy, (3) active or history of DSM-V diagnosis of psychotic, mood, or anxiety disorder, diagnosis of substance abuse or dependence within the last

three months, (4) unstable medical illness, (5) cardiac pacemaker or implanted medication pump, (6) significant neurological disorder or insult, (7) an intracranial implant, (8) any metal present in or near the head, (9) a non-correctable clinically significant sensory impairment, (10) insufficient English language proficiency. All participants gave their written informed consent and the University approved the protocol of the of British Columbia Ethics Committee and in compliance with the Declaration of Helsinki.

2.2 Design

The study employed a double-blind, randomized cross-over design. Participants were randomized to receive either a yoga-tDCS intervention or a yoga-tDCS-sham intervention in a cross-over protocol over two separate days, at least seven days apart. We utilized a stratified randomization scheme using a permuted block method with a random number generator to randomize. Subjects were counterbalanced between the two days of intervention concerning real and sham tDCS. Sham tDCS involved a ramp-up, ramp-down technique in bolstering blinding. Raters were concealed as to whether participants were receiving an active or sham intervention.

2.3 Procedure

Procedures of the first-day visit are shown in Fig. 1A, and the second-day visit was identical except for the screening procedure, which was only conducted during the first-day visit. Participants were screened with the Mini International Neuropsychiatric Interview (MINI) to determine eligibility. After the screening, demographic data were collected, and participants completed the tDCS Safety Screening questionnaire. Before each session, subjects were asked to estimate nicotine, caffeine, alcohol intake, sleep, and over the counter (OTC) compound intake for the 24 hours before the session. The tDCS intervention consisted of 20 minutes of either active or sham tDCS, immediately followed by the yoga part. The yoga part consisted of a one-on-one standardized 40-minute yoga session consisting solely of yoga postures taught by a certified yoga instructor (**Supplementary 1**). Working memory performance and mindfulness were measured before and immediately after the combined intervention condition. The CRQ A, an inventory evaluating side effects associated with tDCS, was completed post tDCS [32].

2.4 Intervention

Electrical direct current was applied through a pair of saline-soaked surface sponge electrodes and delivered through a battery-driven constant current stimulator (Newronika S.p.A, Milano, Italy). The anode was placed with its center over the F3 position (left DLPFC) and the cathode over F4 (right DLPFC) according to the international 10/20 EEG system. Following previous studies, the protocol was selected, suggesting beneficial bilateral DLPFC tDCS for improving WM, including verbal WM [17]. Stimulation was performed for 20 minutes, using an electrode size of 35 cm^2 , a current intensity of 2 mA with 30 seconds ramping up and down, resulting in a current

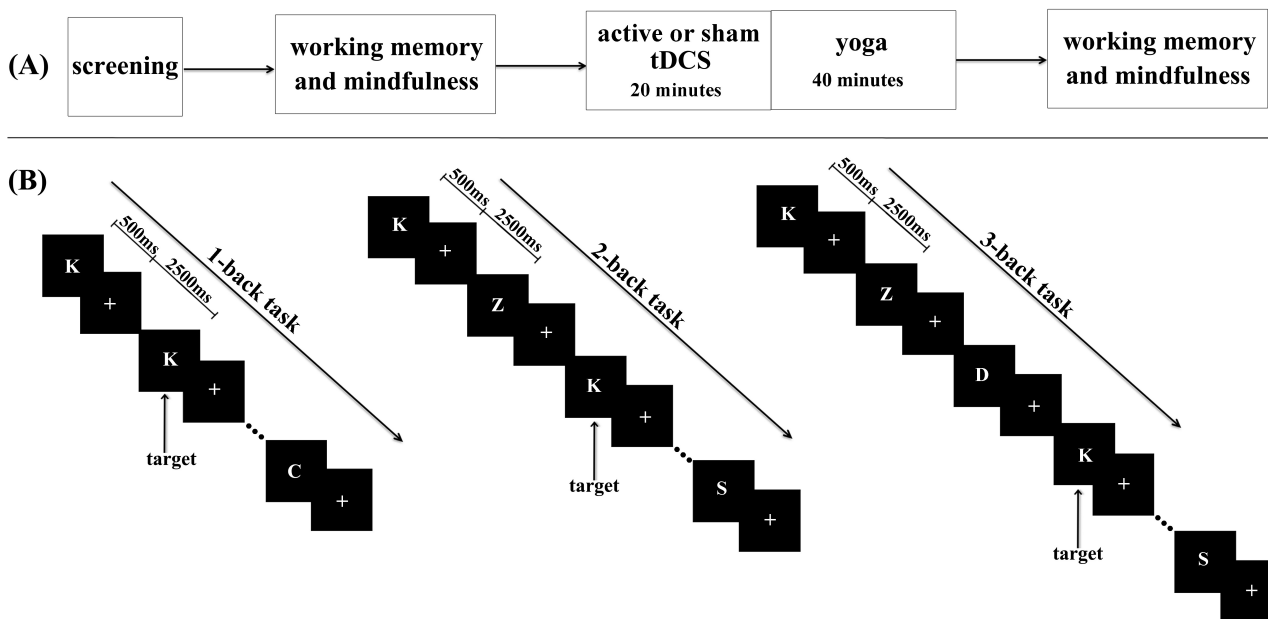


Fig. 1. Schedule of Procedures. (A) Procedures of the visit. (B) The paradigm of the working memory test using 1-back, 2-back and 3-back tasks.

Table 1. Demographic information.

Variable	Category	Value
Sex	Male	14 (63.6%)
	Female	8 (36.3%)
Mean age \pm SD		29.05 (4.56)
Marital status	Never married	17 (77.27%)
	Married	1 (4.55%)
	Divorced	1 (4.55%)
	Domestic Partner	3 (13.63%)
Employment	Student	5 (22.73%)
	Working	17 (77.27%)
	Left	1 (4.55)
Handedness	Right	19 (86.36)
	Ambidextrous	2 (9.09%)

density of 0.08 mA/cm². Sham tDCS consisted of the same electrode placements. However, stimulation intensity was ramped up for the first 30 seconds, followed by a ramp down for 30 seconds, and no further active stimulation [6]. The yoga intervention was a standardized 40-minute one-to-one yoga session consisting of traditional Hatha yoga postures taught by a certified yoga instructor. The posture sequence integrated active movements with mindfulness and was developed in consultation with a certified yoga instructor and literature review [33].

2.5 Outcome measures

2.5.1 Toronto Mindfulness Scale

Toronto Mindfulness Scale (TMS) is a 13 item, two factorial, self-report scale for measuring the mindfulness state (Curiosity, Decentering). It is designed to measure state mindfulness levels, and thus developed for use immediately following meditation. The scale has been validated in several

contexts and has an internal consistency of 0.84–0.88 [34]. The items of factor 1 (Curiosity) reflect an attitude of learning more about one’s experiences. Factor 2 (Decentering) items reflect distancing from identifying personally with thoughts and feelings related to one’s own experience. The scale was developed for a community population and both mindfulness naïve and trained individuals [35].

2.5.2 N-back task

In order to assess working memory, we used the “n-back” letter task. The n-back task provides a simple measure of working memory performance, including response time (RT) for stimulus detection and the rate of correct and error responses. In the “n-back” task, participants are presented with stimuli in temporal order (here letters) and asked to identify stimuli presented n items before. The difficulty of the task is usually varied between 1, 2, and 3-back, which controls for task difficulty. Our study presented participants with letter stimuli (20 capital consonants except the letter ‘X’; Fig. 1B). There were three sequentially presented n-back sessions: 1-back, 2-back, and 3-back. Before each n-back session, an instruction display was presented to inform participants if that block was including a 1-back, 2-back or 3-back task, followed by a 14-letter trial practice session. Each experimental session was comprised of 63 letter trials, and 1/3 were targets. The presentation time for each letter trial was 500 ms, and fixation time (interstimulus interval) was 2500 ms after each letter trial. The total time for each n-back session was 189 seconds. E-Prime software (professional version 2.0, Psychology Software Tools, Pittsburgh, PA) was used to electronically present the stimuli.

Table 2. The mean and standard deviation of measures pre and post-intervention.

Variable	Source		Pre-intervention		Post-intervention	
			Active tDCS	Sham tDCS	Active tDCS	Sham tDCS
			Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Working memory	Accuracy	1-back	0.90 (0.24)	0.98 (0.02)	0.97 (0.05)	0.98 (0.02)
		2-back	0.95 (0.04)	0.95 (0.04)	0.95 (0.04)	0.96 (0.04)
		3-back	0.88 (0.10)	0.91 (0.06)	0.89 (0.10)	0.91 (0.07)
	Reaction time	1-back	704 (512)	606 (151)	574 (146)	596 (151)
		2-back	766 (233)	783 (224)	757 (267)	719 (218)
		3-back	864 (273)	792 (239)	792 (297)	747 (263)
Mindfulness	Curiosity	10.8 (5.6)	11.4 (5.3)	12.6 (5.5)	13.0 (4.5)	
	Decentering	15.5 (6.6)	15.7 (6.4)	18.4 (6.7)	19.5 (5.9)	
	Pain			1.3 (0.6)	1.2 (0.4)	
	Tingling			2.8 (1.8)	3.8 (2.0)	
	Burning			1.7 (1.3)	2.0 (2.0)	
	Fatigue			1.8 (1.6)	2.1 (1.3)	
	Side effects	Nervousness			1.2 (0.5)	1.2 (0.4)
	Concentration			1.3 (0.9)	1.7 (1.4)	
	Visual Perception			1.0 (0.0)	1.2 (0.4)	
	Headache			1.0 (0.0)	1.1 (0.2)	
	Uncomfortable			1.4 (0.5)	1.5 (0.5)	

Note: tDCS, transcranial direct current stimulation; SD, standard deviation.

2.6 Statistical analysis

Statistical analysis was performed using RStudio version 1.2.5019 (RStudio Inc., USA). Descriptive statistics, including means, and standard deviations, were calculated for working memory performance, TMS, and side effects of tDCS and are presented in Table 2. To evaluate the effect of the intervention on working memory performance, a four-way repeated-measures ANOVA was applied on the dependent variables (accuracy and reaction time) with intervention (active vs sham), day (day 1 vs. day 2), time (pre-intervention vs post-intervention), and working memory load (1-back, 2-back, 3-back) as the within-subject factors. A separate three-way repeated-measures ANOVA was applied on mindfulness outcome variables (curiosity, decentering) with intervention (active vs sham), day (day 1 vs. day 2), and time (pre-intervention vs post-intervention) as the within-subject factors. For working memory, four-way interaction effects of intervention, day, time, and working memory load were not statistically significant. To address this, three-way interaction effects were employed in the ANOVA model. The homogeneity of variances and normal distribution of data was tested with boxplot methods and the Shapiro-Wilk normality test. In addition, missing data were imputed by using the imputation method. Mauchly's test was used to evaluate the sphericity of the data before performing the repeated measures ANOVA. If the assumption of sphericity was violated, degrees of freedom were corrected via Greenhouse-Geisser estimates of sphericity. In case of significant interaction and main effects ($P < 0.05$), pairwise comparisons were conducted with Bonferroni-corrected post-hoc t -tests.

3. Results

3.1 Data overview

Participants were predominately male ($n = 14$, 63.64%), right-handed ($n = 19$, 86.36%) and single ($n = 17$, 77.27%) (Table 1). The average age of participants was 29.05 ± 4.56 years. The mean and standard deviation of working memory and mindfulness outcome measures are summarized in Table 2.

3.2 N-back

No significant interaction of intervention by time by day by working memory load was found for performance accuracy and response time (Fig. 2 and Table 3). There was, however, a statistically significant interaction of day by intervention by working memory load on average reaction time ($F_{2,219} = 5.06$, $P = 0.007$), and a significant main effect of time ($F_{1,219} = 5.94$, $P = 0.016$), with longer reaction time noted post-intervention in comparison to pre-intervention (Table 3). The pairwise comparisons conducted by paired t -tests revealed a significantly longer reaction time for the active compared to the sham tDCS condition for the 3-back load at day 1 ($P = 0.012$), but not for other combinations of working memory load and day. There was also a statistically significant interaction of day by time by working memory load on accuracy ($F_{2,231} = 5.123$, $P = 0.002$). The pairwise comparison showed a significantly higher accuracy post-intervention than pre-intervention for the 3-back load at day 2 ($P = 0.017$).

3.3 Mindfulness

There was a significant time effect for both the curiosity facet of mindfulness ($F_{1,65} = 6.359$, $P = 0.014$) and the decentering facet of mindfulness ($F_{1,65} = 24.78$, $P \leq 0.001$), with

Table 3. Results of repeated-measures ANOVA for the effects of combined tDCS and yoga on working memory and mindfulness.

Task	Outcome measure	Source	<i>df</i>	<i>F</i>	<i>P</i>	πp^2
Working memory	Accuracy	Day	1,231	39.72	< 0.001	0.147
		Time	1,231	0.581	0.447	0.003
		WM load	2,231	93.18	< 0.001	0.447
		Day × time	1,231	10.58	0.001	0.044
		Time × WM load	2,231	0.157	0.855	0.001
		Day × WM load	2,231	20.88	< 0.001	0.153
		Day × time × WM load	2,231	6.123	0.003	0.050
	RT	Intervention	1,230	0.084	0.360	0.004
		Time	1,230	5.942	0.016	0.025
		WM load	2,230	67.67	< 0.001	0.037
		Day	1,230	11.82	0.001	0.049
		Intervention × day	1,230	0.843	0.360	0.004
		Day × WM load	2,230	4.506	0.012	0.038
		Intervention × WM load	2,230	3.363	0.036	0.028
Mindfulness	Curiosity	Intervention × day × WM load	2,230	5.063	0.007	0.042
		Time	1,59	6.243	0.015	0.096
		Day	1,59	0.321	0.573	0.005
		Intervention	1,59	0.028	0.868	0.000
		Time × Day	1,59	1.360	0.248	0.023
		Day × Intervention	1,59	0.003	0.954	0.000
		Time × Intervention	1,59	0.090	0.765	0.002
	Decentering	Time × Day × Intervention	1,59	1.519	0.223	0.025
		Time	1,59	25.90	< 0.001	0.305
		Day	1,59	2.150	0.148	0.035
		Intervention	1,59	0.744	0.392	0.012
		Time × Day	1,59	2.976	0.090	0.048
		Day × Intervention	1,59	0.523	0.472	0.009
		Time × Intervention	1,59	1.257	0.267	0.021
	Time × Day × Intervention	1,59	0.268	0.607	0.005	

Note: tDCS, transcranial direct current stimulation; RT, reaction time; WM, working memory; Significant results are highlighted ($P < 0.05$) in bold.

higher curiosity and decentering pre-intervention in comparison to post-intervention (Fig. 2 and Table 3). Other factors, such as intervention, day, and respective interaction effects, were not statistically significant.

4. Discussion

To the best of our knowledge, this is the first study to date to explore a combination of tDCS and yoga using a randomized, sham-controlled, double-blind design. We investigated the effect of active tDCS targeting the DLPFC bilaterally, combined with yoga on measures of mindfulness and working memory performance in twenty healthy individuals. While these interventions have individually been shown to respectively impact working memory and mindfulness, and other studies with similar combined interventions showed encouraging results, the current combined therapy protocol did not significantly affect a sham tDCS control condition.

There are multiple potential explanations for this, including a small sample size, which may have limited the power to detect a difference. Moreover, while the results of [28] suggest that a combination of tDCS and meditation improves

working memory compared to a sham tDCS plus psychoeducation, that study did not delineate whether the effect on working memory was attributable to meditation or tDCS. Moreover, [28] involved subjects who were naïve to meditation. Meditation was combined with online tDCS and involved repeated interventions over four weeks. Alternatively, it is also possible that the two interventions, yoga & tDCS, unlike specific styles of meditation and tDCS, do not act synergistically or potentially may have negated their respective individual effects. While our yoga intervention was a Hatha yoga-based practice, which coupled physical movements with mindful breathing, there was no formal meditation. Given the predominance of physical movement over meditation, the yoga intervention may have been more likely to activate motor regions than the prefrontal regions of the cortex, which may also account for our findings compared to previous studies involving specific meditation interventions.

Moreover, the specific cortical regions modulated by the respective intervention (e.g., prefrontal vs. motor areas) and the aftereffects of tDCS on cortical excitability have different durations, depending on the specific stimulation proto-

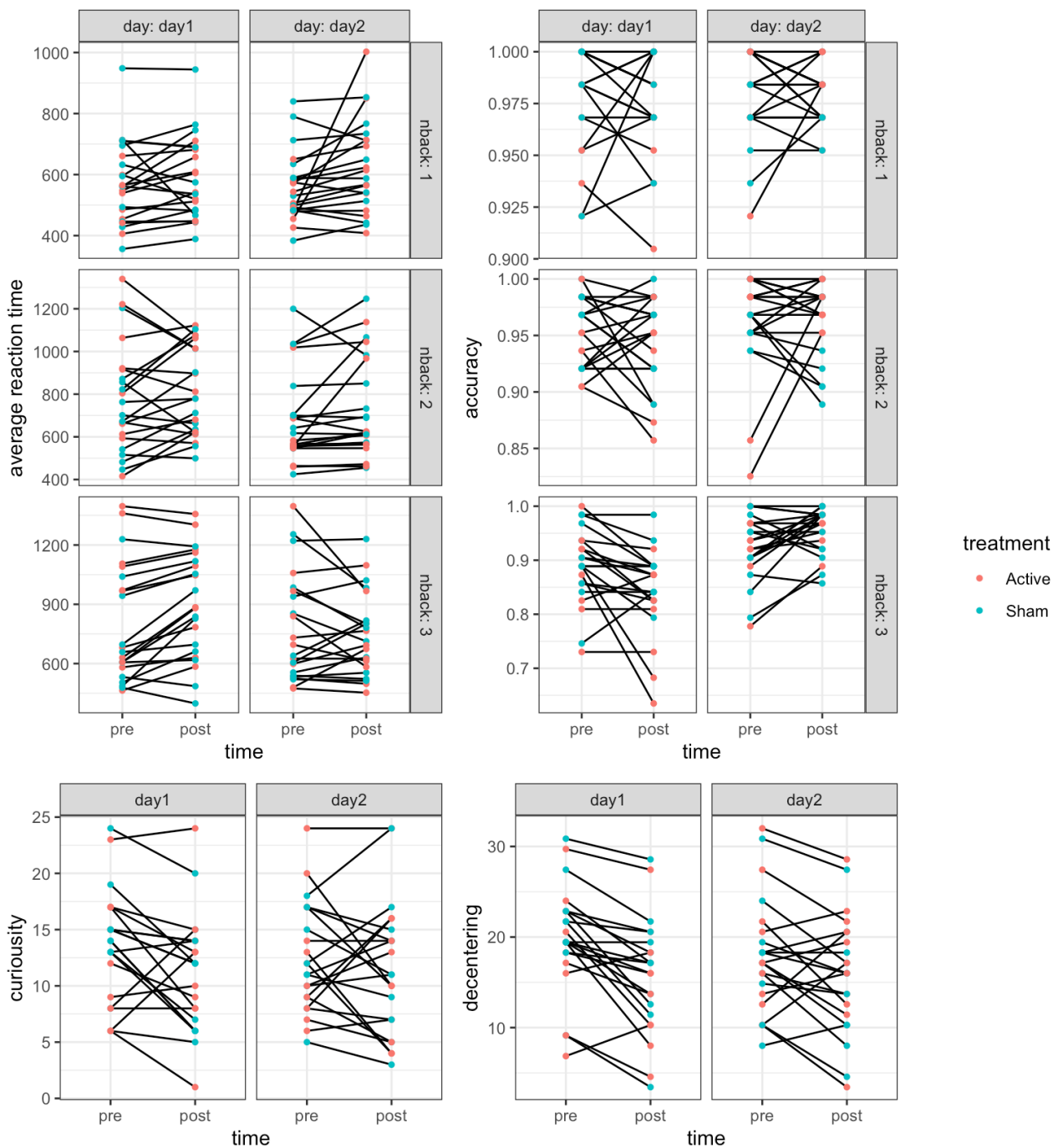


Fig. 2. Comparison of combined tDCS and Yoga on working memory performance and mindfulness pre-post intervention concerning different days and different N-back task versions.

col relevant. Concerning the latter, findings from physiological studies show that tDCS aftereffects on motor cortical excitability induced by the same stimulation intensity/duration (2 mA, 20 minutes) can last differentially over the time course following the intervention [36]. Specifically, a significant increase of excitability in the motor cortex was shown up to 30 minutes following tDCS, which diminished at 60-minute post tDCS and re-established again at 90-minute and 120-minute post tDCS [36]. Considering that measurements in

the present study occurred after the yoga intervention (40-minute duration), it could be the case that tDCS induced excitability enhancement; however, this was diminished during the time of measurement. This could be a potentially confounding factor which needs to be considered in future studies. To rule this out, we ideally need a tDCS only condition to compare its effects with the tDCS + yoga which our study lacked.

While active vs. sham tDCS combined with yoga had no impact on working memory or mindfulness, the day of intervention did significantly affect both outcome measures. The decentering facet of mindfulness and accuracy of 3-back working memory performance significantly improved pre-post intervention on the first day of the intervention compared to the second day of the intervention. This could be because that the practice block in the WM task did not include enough trials for achieving a stable performance.

Some limitations to the current study require consideration. These include the small sample size, which caused a relatively low power to reliably detect changes of the employed measures. The generalizability of the findings is limited given that it was a single site and included predominantly white and single participants. Moreover, we did not control for handedness. However, most subjects were right-handed, neither excluded smokers, which may have been a factor as nicotine has been shown impact cortical excitability and tDCS modulatory effects. Furthermore, while experimental sessions were separated by at least one week, carry-over effects are not entirely excluded. Unlike previous research, where tDCS was conducted online during the meditation, our study was offline with the yoga component following tDCS. Finally, the addition of specific control conditions (e.g., non-yoga physical activity + active tDCS, non-yoga physical activity + sham tDCS) would have been advantageous for interpreting the study results.

5. Conclusions

Our preliminary results show yoga and tDCS individually impact working memory and mindfulness but do not support a benefit combined yoga and tDCS. Several protocol specifics and study limitations may explain these findings. In general, more research is needed to help delineate the impact of yoga and tDCS on working memory and mindfulness.

Author contributions

MD & FVR conceived, designed and coordinated the study; all authors contributed to the data analysis; all authors contributed to the writing and editing of the paper.

Ethics approval and consent to participate

All participants gave their written informed consent, and the University approved the protocol of the British Columbia Ethics Committee and in compliance with the Declaration of Helsinki.

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Conflict of interest

The authors declare no conflict of interest.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at <https://jin.imrpress.com/EN/10.31083/j.jin2002036>.

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