

# Time Dependent Effects of Transcranial Direct Current Stimulation and Caffeine on Vigilance Performance During Extended Wakefulness

R. Andy McKinley<sup>1</sup>(✉), Lindsey K. McIntire<sup>2</sup>, Ryan Schilling<sup>3</sup>,  
Chuck Goodyear<sup>2</sup>, and Justin Nelson<sup>2</sup>

<sup>1</sup> Applied Neuroscience Branch, 711th HPW, 2510 Fifth Street, BLDG 840,  
Dayton, OH, USA

Andy.McKinley@wpafb.af.mil

<sup>2</sup> Infoscitex Inc., Dayton, OH, USA

<sup>3</sup> ORISE, Dayton, OH, USA

**Abstract. Background:** Previously, we found that transcranial direct current stimulation (tDCS) preserved vigilance performance approximately twice as well and three times as long as caffeine during a period of extended wakefulness. Vigilance performance often declines linearly over the period of watch, but in our previous study the performance trends over the period of watch were not analyzed. Hence, it was not known whether the intervention applied reduced the vigilance decrement, or simply shifted the performance to a higher mean value while maintaining a similar slope.

**Objective:** Our objective was to evaluate the time-dependent effects (within each period of watch) of anodal transcranial direct current stimulation (tDCS) applied to the pre-frontal cortex at 2 mA for 30 min. We then compared these results to those of caffeine as well as the effects of both interventions on arousal.

**Methods:** The period of watch was segregated into equal time segments and target identification accuracy was averaged across subjects in each group. These values were used in an analysis of covariance (separately for each session) as the dependent variable. Factors were group and subject nested in group.

**Results:** The results indicated there is not a significant difference in slope (i.e. vigilance decrement) between the treatment conditions (tDCS, caffeine, and sham) within each period of watch. However, as reported previously, there was a significant difference in mean change from baseline between the treatment conditions.

**Conclusion:** Our data suggests that tDCS does not prevent the vigilance decrement within the period of watch. Rather, it shifts performance to higher mean values by a scalar multiple while maintaining a similar slope.

**Keywords:** Transcranial direct current stimulation · Sleep deprivation  
Caffeine · Cognition · Vigilance

## 1 Introduction

As work demands and pressures continue to increase, sleep deprivation induced fatigue has continued to plague many occupations. Notably, sleep deprived individuals suffer from cognitive performance declines analogous to being legally intoxicated [1] as well as undesired mood states such as increased hostility and anger [2]. In particular, vigilance and psychomotor reaction times are highly susceptible to performance losses during periods of sleep-deprivation or extended wakefulness [3, 4]. Caffeine is perhaps the most readily available and commonly used stimulates to assuage the effects of sleep deprivation. However, caffeine has many limitations. As the period of sleep deprivation increases, individuals often require greater doses to have the desired effects in subjective feeling of drowsiness and fatigue. However, in high doses (above 400 mg) caffeine can cause caffeine intoxication, an undesirable condition with symptoms such as declines in mood, insomnia, nervousness, hallucinations, and intestinal complaints [5–7]. Likewise, the effect is reduced as the level of sleep deprivation increases [8] while the effects are short-lived (i.e. less than 2 h) [3]. Chronic use further reduces its beneficial effects [9]. As a result, we have begun to investigate other means of preserving performance when sleep deprived, such as non-invasive brain stimulation.

Recently, we have discovered that observed linear declines in vigilance performance over time, known as the vigilance decrement [10], can be reduced or eliminated with a form of non-invasive brain stimulation known as transcranial direct current stimulation (tDCS) [11]. This technique applies weak currents between two electrodes placed on the scalp, although the reference electrode is sometimes placed in an extracephalic location [12–14]. The stimulation is believed to modulate activity in a polarity dependent manner, which can have beneficial effects on performance [12, 13]. In a previous study, we found just 30 min of tDCS applied to the dorsal-lateral prefrontal cortex (DLPFC) prevented vigilance performance declines for up to 6 h in participants who were kept awake for 30 h [3]. However, the exact mechanism causing this effect remains somewhat ambiguous. To examine this further, it is necessary to first understand existing theories regarding the vigilance decrement.

Currently, arousal theory and resource theory are the two primary competing theories that attempt to explain the vigilance decrement [15]. Arousal theory attributes the increased rate of missed critical signals to a reduction in overall arousal (i.e. the participant becomes uninterested) while resource theory contends the performance drop is driven by depletion of some critical cognitive resource [15, 16]. Previously, we concluded that tDCS supported the resource theory due in part to the fact that we did not observe a significant change in response bias. Modulating arousal generates a significant increase in response bias (i.e. increases in target detections and false alarms). However, we only found significant increases in signal (i.e. target) detection that was not accompanied by increases in false alarms [3]. Of note, vigilance performance was assessed by taking the cumulative signal detection percentage over the entire session essentially making each session a signal data point. Hence, we did not examine the trends within a session which is more commonly the case in the vigilance literature. To further assess how tDCS is creating the previously observed performance improvements, we decided to decompose the data within each session and examine possible trends.

The first possibility was that tDCS produces its beneficial effect by reducing or eliminating the negative slope of the vigilance decrement curve. In fact, Nelson found this to be the case in fully rested participants [11]. The other possibility is that tDCS simply shifts the vigilance curve to higher values by a scalar factor without impacting the overall slope. Hence, by starting at a higher level of performance at beginning of the vigil, the participant could achieve a higher level of number of signal detections while also having a performance decrement within the individual session. To answer this question, we reanalyzed the data to examine the effects within each session.

## 2 Methods and Materials

### 2.1 Procedures

The original data set from our previous publication was further analyzed and reported herein. For details on the original methods and procedures used to collect the data set, please see McIntire et al. [3].

### 2.2 Analysis

The Mackworth clock test data collected in McIntire et al. [3] were further decomposed into temporal segments within each session and analyzed. Only sessions occurring during or after the intervention was applied were included (i.e. sessions occurring at 4 am, 6 am, and 8 am). The 10 am session was not included due to the fact circadian rhythms had shifted in a positive direction creating improvements in performance not influenced by the intervention applied. Each 30 min session contained a total of twelve targets. The signal (i.e. critical target) detection accuracies were segregated into three time segments with 4 targets in each segment. These accuracies were then averaged within each segment for each subject. Slopes were calculated with a simply linear fit. To quantify the effect of the intervention (i.e. tDCS or caffeine) on the slope of the vigilance decrement, these accuracy values were used in an analysis of covariance (separately for each session) as the dependent variable. Factors were group and subject nested in group. Time segment (coded as 1, 2, 3) was used as a covariate. The p-values reported are from an F-test for the group\*segment interaction.

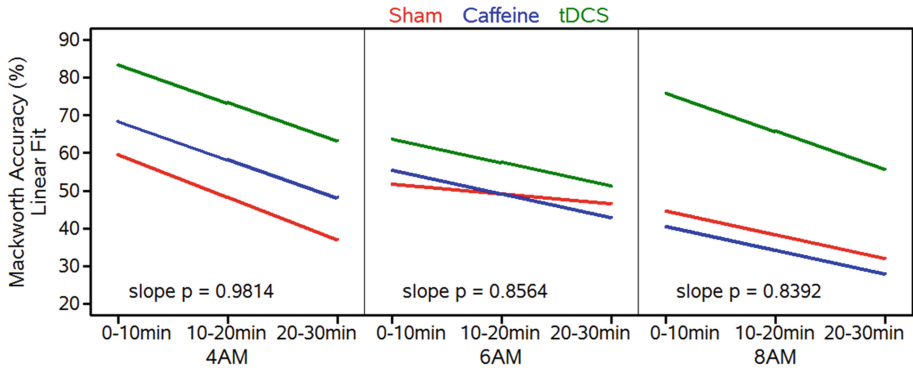
A second analysis was used to examine effects on accuracy levels (i.e. shifts in performance). Each subject had an accuracy mean ( $n = 12$ ) for each session (2 am, 4 am, 6 am, 8 am). For each subject, the change in mean accuracy from 2 am to each subsequent session was used as the dependent variable in a one-way analysis of variance (separately for each session) with group as the factor. The p-value is from an F-test for the main effect of group.

## 3 Results

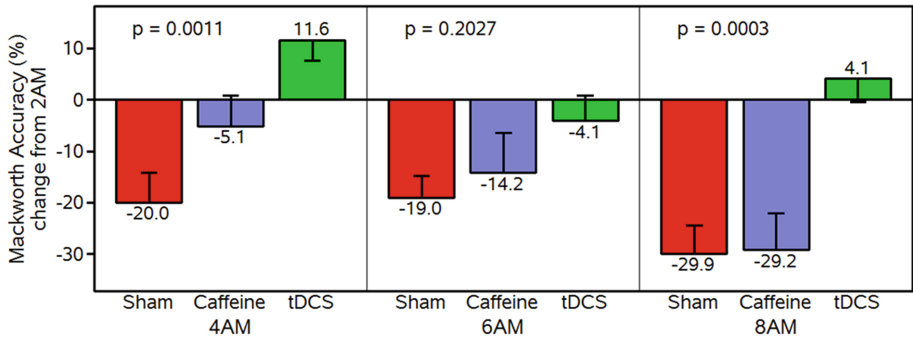
### 3.1 Mackworth Clock Test

There were no significant differences in slope between the three treatment groups for any of the sessions tested as denoted by the F-test. Figure 1 displays the linear fit slopes

for each session along with the p-values for the group\*segment interaction. However, similar to the results presented the original study, we did find significant main effect of group in the mean percentage change from baseline (i.e. 2 am session) in both the 4 am ( $p = .001$ ) and 8 am ( $p = .003$ ) sessions. The post hoc t-tests showed that the tDCS group performed significantly better than both the sham and caffeine groups in both 4 am and 8 am sessions. The sham and caffeine groups were not statistically different from one another in either session (Fig. 2).



**Fig. 1.** Mackworth clock test accuracy slopes for the 4 am, 6 am, and 8 am sessions. The 4 am session denotes the time point at which the intervention was applied. Slopes were the result of a linear fit to the accuracy percentages in each of the three time segments.



**Fig. 2.** Mackworth clock test accuracy mean change from 2 am (Baseline). Caffeine was given at 3:15 am (requires 1 h to be fully effective); tDCS was applied at 4 am. Changes in performance were measured for each subject and averaged across groups ( $n = 10$ ).

## 4 Discussion

We previously discovered large effects of anodal tDCS applied to the DLPFC on vigilance performance that remained over a period of hours. However, we did not examine the effects within sessions as such analyses are not common in the

fatigue/sleep deprivation literature. Still, the vigilance decrement is typically found within the vigil itself begging the question of whether the effects of tDCS manifested in a reduction of the vigilance decrement (i.e. performance slope), or whether it improved performance overall (i.e. shifting the performance values to higher levels at each time point) without influencing the slope.

The results reported herein seem to suggest the latter as there were no significant differences in the slope of the vigilance decrement between groups. As reported in our original publication [3], there was a significant difference between groups in mean performance during the 4 am and 8 am sessions with tDCS seemingly eliminating the effects of sleep-deprivation induced fatigue on vigilance completely. For reference, the intervention (caffeine or tDCS) was applied in a manner that its greatest effect would be present during the 4 am session.

Previously, we found that tDCS applied in a bilateral DLPFC electrode configuration for only 10 min removed the vigilance decrement in fully rested individuals for at least 20 additional minutes [11]. The results also suggested the anodal tDCS applied to the left hemisphere produced better performance during the period of stimulation however the differences were slight. This, in part, influenced the electrode scalp location used in this study.

The difference was that the cathode was placed on the contralateral bicep in an effort to maximize the delivered intensity. Physics dictates that electricity will follow the path of least resistance; hence it will flow more easily through lower resistance tissues such as the skin and cerebral spinal fluid before entering brain tissue. Theoretically, by placing the electrodes close together, the current will remain superficial, reducing the intensity of the electric field delivered to the cortical tissue. Conversely, by placing the electrodes far apart, the current is forced to take a longer pathway through the brain, thereby increasing electric field intensity. This extracephalic configuration style has produced rather large effects in previous studies [3, 17, 18].

The results of the analyses from the current study suggest a different effect within the vigil than reported in Nelson et al. [11]. These differences may have been a result of a difference in vigilance tasks indicating the effects are task specific. The differences may also have been caused by the difference in electrode montage (i.e. extracephalic vs. bilateral). It may instead be induced by the addition of the fatigue stressor. Hence, rather than preventing the vigilance decline, individuals are actually benefiting from a much larger recuperation during breaks creating a higher level of performance at the start of the next vigil.

Interestingly enough, all three groups maintained a very similar vigilance decrement slope in each of the sessions considered in this study. In this way, both caffeine and tDCS produced the same type of benefit where performance was increased at the start of the vigil, but suffered from a linear decline over time. This consistency between the treatments may suggest similar mechanisms of action, as reported in our previous manuscript [3]. It does appear that when sleep deprived, neither intervention is capable of preventing the vigilance decrement. Even with these similarities, the results still show a differential effect on mean performance over longer timelines (i.e. multiple sessions). This difference is better explained by resource theory given that there was no change in response bias and a separate test of arousal showed no difference in performance between the caffeine and tDCS groups [3]. If the effect were due to arousal

alone, the effects on vigilance should have been the same in the tDCS and caffeine groups.

This study has potentially raised more questions than it has answered. The robustness of the effects of tDCS on vigilance should be examined across tasks to test for sensitivity to the task itself. Likewise, the extracephalic electrode configuration should be replicated in a study of rested individuals to look for consistency in the findings reported in Nelson et al. [11]. However, the current results may have significant implications for scheduling and duty cycle for many occupations, if the effects of tDCS are actually derived from improved recuperative value of the breaks. Regardless, these results warrant further investigation of tDCS as an intervention for fatigue.

**Acknowledgments.** We'd like to acknowledge the Air Force Office of Scientific Research for funding this project. A special thanks to our entire research team for working so quickly and tirelessly through this process.

**Financial Disclosures.** None of the authors have any financial disclosures or conflicts of interest.

## References

1. Williamson, A.M., Feyer, A.M.: Moderate sleep deprivation produces impairments in cognitive and motor performance equivalent to legally prescribed levels of alcohol intoxication. *Occup. Environ. Med.* **57**, 649–655 (2000)
2. Hart, R.P., Buchsbaum, D.G., Wade, J.B., Hamer, R.M., Kwentus, J.A.: Effect of sleep deprivation on first-year residents' response times, memory, and mood. *J. Med. Educ.* **62**, 940–949 (1987)
3. McIntire, L.K., McKinley, R.A., Goodyear, C., Nelson, J.: A comparison of the effects of transcranial direct current stimulation and caffeine on vigilance and cognitive performance during extended wakefulness. *Brain Stimulation* **7**, 499–507 (2014)
4. Lim, J., Dinges, D.F.: Sleep deprivation and vigilant attention. *Ann. N.Y. Acad. Sci.* **1129**, 305–322 (2008)
5. Griffiths, R.R., Bigelow, G.E., Liebson, I.A.: Reinforcing effects of caffeine in coffee and capsules. *J. Exp. Anal. Behav.* **52**(2), 127–140 (1989)
6. Stern, K.N., Chait, L.D., Johanson, C.E.: Reinforcing and subjective effects of caffeine in normal human volunteers. *Psychopharmacology* **98**, 81–88 (1989)
7. Loke, W.H., Hinrichs, J.V., Ghoneim, M.M.: Caffeine and diazepam: separate and combined effects on mood, memory, and psychomotor performance. *Psychopharmacology* **87**, 344–350 (1985)
8. McLeelan, T.M., Kamimori, G.H., Voss, D.M., Bell, D.G., Cole, K.G., Johnson, D.: Caffeine maintains vigilance and improves run times during night operations for special forces. *Aviat. Space Environ. Med.* **76**, 647–654 (2005)
9. Miller, N.L., Matsangas, P., Shattuck, L.G.: Fatigue and its Effect on Performance in Military Environments. Naval Postgraduate School Operation Research Department (Report No. 0704-0188) Monterey, CA (2007)
10. Davies, D.R., Parasuraman, R.: *The Psychology of Vigilance*. Academic Press, London (1982)

11. Nelson, J.T., McKinley, R.A., Golob, E.J., Warm, J.S., Parasuraman, R.: Enhancing vigilance in operators with prefrontal cortex transcranial direct current stimulation (tDCS). *NeuroImage* **15**(85), 909–917 (2014)
12. Paulus, W.: Outlasting excitability shifts induced by direct current stimulation of the human brain. *Adv. Clin. Neurophysiol.* **57**, 708–714 (2004)
13. Priori, A.: Brain polarization in humans: a reappraisal of an old tool for prolonged non-invasive modulation of brain excitability. *Clin. Neurophysiol.* **11**(14), 589–595 (2003)
14. McKinley, R.A., Weisend, M.P., McIntire, L.K., Bridges, N., Walters, C.M.: Acceleration of image analysts training with transcranial direct current stimulation. *Behav. Neurosci.* **127**(6), 936–946 (2013)
15. Nelson, J.T.: Modulating the dorsolateral prefrontal cortex during sustained attention. Unpublished doctoral dissertation, Tulane University (2012)
16. Smit, A.S., Eling, P.A., Coenen, A.M.: Mental effort causes vigilance decrease due to resource depletion. *Acta Psychol.* **115**(1), 35–42 (2004)
17. McKinley, R.A., Weisend, M.P., McIntire, L.K., Bridges, N., Walters, C.M.: Acceleration of image analysts training with transcranial direct current stimulation. *Behav. Neurosci.* **127**(6), 936–946 (2013)
18. McKinley, R.A., Nelson, J.T., McIntire, L.K., Nelson, J., Weisend, W.: Improved skill learning: enhancing formation and retention of non-declarative memories with transcranial direct current stimulation. Presented at the Society for Neuroscience, New Orleans, LA, Oct 2012