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14. ABSTRACT
Military personnel endure rigorous and demanding man-hours designated to monitoring and locating targets in tasks such as cyber defense and Unmanned Aerial Vehicle (UAV) operators. These tasks are monotonous and repetitive, which can result in vigilance decrement. The objective of the study was to implement a form of noninvasive brain stimulation known as transcranial DC stimulation (tDCS) over the left frontal eye field (LFEF) region of the scalp to improve cognitive performance. The participants received anodal and cathodal stimulation of 2 mA for 30 min as well as placebo stimulation on 3 separate days while performing the task. The findings suggest that anodal and cathodal stimulation significantly improves detection accuracy. Also, a correlation was detected between percent of eye closure (PERCLOS) and blinking frequency in relation to stimulation condition. Our data suggest that tDCS over the LFEF would be a beneficial countermeasure to mitigate the vigilance decrement and improve visual search performance.

15. SUBJECT TERMS
Transcranial direct current stimulation, tDCS, neuromodulation, noninvasive brain stimulation, cognitive enhancement, visual search cognitive support, human performance, augmentation, ISR

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Augmenting Visual Search Performance With Transcranial Direct Current Stimulation (tDCS)

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Military personnel endure rigorous and demanding man-hours designated to monitoring and locating targets in tasks such as cyber defense and Unmanned Aerial Vehicle (UAV) operators. These tasks are monotonous and repetitive, which can result in vigilance decrement. The objective of the study was to implement a form of noninvasive brain stimulation known as transcranial DC stimulation (tDCS) over the left frontal eye field (LFEF) region of the scalp to improve cognitive performance. The participants received anodal and cathodal stimulation of 2 mA for 30 min as well as placebo stimulation on 3 separate days while performing the task. The findings suggest that anodal and cathodal stimulation significantly improves detection accuracy. Also, a correlation was detected between percent of eye closure (PERCLOS) and blinking frequency in relation to stimulation condition. Our data suggest that tDCS over the LFEF would be a beneficial countermeasure to mitigate the vigilance decrement and improve visual search performance.

Keywords: frontal eye field (FEF), percent of eye closure (PERCLOS), sustained attention, transcranial DC stimulation (tDCS), vigilance

Human performance metrics have been evaluated in previous research studies to determine the cognitive ability of an operator during a vigilance task (Klingner, Tversky, & Hanrahan, 2011; Upadhyay & Singh, 2013; Pattyn, Neyt, Henderickx, & Soetens, 2008). A vigilance task is described as a task that an operator can perform without difficulty for a short period of time, however as time on the task increases the operator's performance becomes impaired or degrades. This impairment of the human operator performance is known as a "vigilance decrement" (Verster & Roth, 2013). During a vigilance decrement, the operator experiences either a decrease in correct detections over time or an increase in reaction time (RT) (Helton & Russell, 2011). The vigilance decrement is commonly a result from mental demand or cognition overload during a monotonous and repetitive task (Finomore et al., 2013). With the excess of mental demand and cognitive workload on an operator, the desired performance on a specific task will begin to diminish. In military operations, cognitive performance is instrumental to ensure that the operators perform their designated tasks to their best ability. If an error occurs or a threat is not detected, it could result in serious repercussions. Operator performance has always been at the forefront of the Air Force mission. However, with an increase in workload on the operators within the past several years, the demand of optimizing the performance has

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become a key focus. For this reason, it is imperative to determine whether modifications to the operator's cognitive ability could result in an improvement in detection accuracy and response time during a monotonous task.

Various remedies have been evaluated in an attempt to mitigate the vigilance decrement during a monotonous task. Previous research studies have provided the operator's with chewing gum or caffeinated beverages (Morgan, Johnson, & Miles, 2014; Temple et al., 2000) during a vigilance task in efforts to improve performance. When the operator was provided with chewing gum during a vigilance task (Morgan et al., 2014), target detection and response time improved. However, these improvements in the operator's performance were only displayed in the latter stages of the task. On the other hand, when the operator was provided with caffeinated beverages (Temple et al., 2000), the overall percent of target detection displayed a decrement. Moreover, the participants who received caffeine did perform at a higher level compared to the participants who received noncaffeinated beverages but a decrement still occurred. Both of these remedies provided positive feedback on the operator's performance compared to the sham condition. Our efforts are expecting to determine whether providing noninvasive brain stimulation may prove to be a more adequate solution in reducing vigilance during a monotonous task.

A form of noninvasive brain stimulation known as transcranial DC stimulation (tDCS) was first introduced in the medical realm. This technology was used for patients undergoing treatment for major depressive disorders (Martin et al., 2011), stroke rehabilitation (Fusco et al., 2013), and Parkinson's disease (Benninger et al., 2010), just to name a few. It was also discovered that the healthy control patients who received transcranial DC stimulation showed a cognitive benefit (Boroojerdi et al., 2001). As of late, there has been recent interest in the use of tDCS on healthy participants to improve human performance and cognition. The application of tDCS has been administered over the prefrontal cortex to improve working memory and accelerated learning (Andrews et al., 2011; Hoy et al., 2013; Martin et al., 2013). In a recent study, it has been shown that applying anodal stimulation over the dorsal-lateral prefrontal cortex accelerated the training time for image analyst (McKinley et al., 2013). In doing so, it provided evidence that this technology could be used to accelerate learning and reduce errors during a monotonous task. Another study was conducted using tDCS over the prefrontal cortex to enhance vigilance in operators during a repetitive task (Nelson et al., 2014). The findings suggested that applying tDCS over the prefrontal cortex improved target detection performance which was the primary metric for vigilance. Because there were no significant changes in the number of false alarms, the authors reasoned that the effects on vigilance were not simply attributable to an overall increase in arousal. This was later confirmed by McIntire, McKinley, Goodyear, and Nelson (2014), where tDCS was shown to have a larger and longer lasting benefit in vigilance performance when compared with caffeine. Again, there were no effects of tDCS on false alarms. Further, there was no difference in effect between tDCS and caffeine in a RT test, which served as a test of arousal. Because caffeine and tDCS acted differently on vigilance performance and arousal, the effects on vigilance could not be explained by changes to arousal alone. The authors stated that the effects are likely attributable to changes in available cognitive resources.

The tDCS technique delivers a very weak electrical current (usually 1 to 2 mA) by way of electrodes applied to the scalp to modulate cortical excitability. Traditionally, one electrode is placed on a scalp location over the brain region to be modulated, whereas the other electrode is placed over an brain region not involved in the active neural network or on an extracephalic site. The amount of current administered is too weak to directly cause neurons to fire, although it can modulate underlying neuronal activity. A meta-analyses conducted by Brunoni & Vanderhasselt (2014) confirms that the application of the anodal electrode over the scalp will slightly depolarizes the membrane potential of the underlying cortical neurons thereby making it easier for them to fire. The net result is an increase in spontaneous activity and local excitability. Reversing the polarity has been reported to have the opposite effect, at least over the motor cortex (Brunoni & Vanderhasselt, 2014; Priori, 2003). This has led to the belief that tDCS can increase or decrease regional brain activity in a polarity specific manner. However, outside the motor cortex, the effects may not be as straightforward. A recent meta-analysis concluded that cathodal tDCS rarely produced the opposite effect of anodal tDCS on cognitive tasks when applied outside the motor cortex (Jacobson, Koslowsky, & Lavidor, 2012). In our own work, we have observed a similar trend. We demonstrated that both polarities of tDCS (anodal and cathodal) yielded similar effects in a vigilance task (Nelson et al., 2014). Therefore, it was hypothesized that there would be no difference in the cognitive effects between anodal and cathodal stimulation in the experiment reported herein.

In this study, we are applying tDCS to the left frontal eye field (LFEF) region using anodal, cathodal, and sham conditions during a visual search task. The frontal eye field region is involved in processing visual information (Jaun-Frutiger et al., 2013). It has also been shown that attentional orienting, saccades programming, and visual search have been linked to the frontal eye field activity (Ronconi, Basso, Gori, & Facoetti, 2014). The left frontal eye field (LFEF) was selected in this study because of the handedness of our research participant population. In a functional imaging study, it was shown that activation of the left prefrontal cortex was superior compared to the right prefrontal cortex during a cognitive task for right-handed participants (Schambra et al., 2011). Because our research participants were right-handed, we selected the left frontal eye field region for the stimulation site. However, providing stimulation to the right frontal eye field may also be effective in augment cognitive performance during a visual search task. Our efforts in this study attempt to mitigate the vigilance decrement by using tDCS over the LFEF region to increase functional activity. In doing so, we expect to concur with previous evidence that using tDCS is beneficial to cyber defense operator, air traffic controllers, remote piloted aircraft operators and the overall air force mission.

Method

Participants

A total of 12 active duty military participants were recruited for the study, however one of the participants withdrew. Of the 11 participants who completed the study, 6 were male and 5 were female. The age for the participants ranged from 24 to 42 years old (mean age of 31.7). The study was completely voluntary and the participants could withdraw at any time if they wished to do so. Participants were excluded from the study if they had any neurological or psychological disorders, problems with motor coordination, head trauma, high blood pressure, or were color deficient. Female participants were also excluded if they were pregnant or planning to become pregnant during the duration of the study. Compensation of $20/hour was provided to the participants as well as an Air Force coin at the completion of the study.

Vigilance Task

The vigilance task that was performed during this study involved a visual search detection paradigm. The task took place in our laboratory at Wright-Patterson Air Force Base using a standard desktop computer (Samsung 173s 17″ monitor). In essence, when the program began, a screen appeared randomly displaying 80 blue circles and 80 red squares. Over the duration of the task, 25% of the images displayed a random red circle, this was the objective target. If the participant observed the red circle on the screen they responded by pressing on the enter button on the keyboard. If they did not observe the red circle on the screen, they responded by pressing the spacebar on the keyboard. The images were on the screen for a duration of 7 seconds and there was a 1.5 second break between images. During the break phase, a crosshair was represented in the middle of the screen which allowed each participant to refocus before the next trial began. The overall task had a duration of 30 minutes. (See Figure 1 for representation of the task)

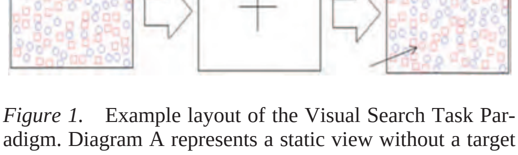

Figure 1. Example layout of the Visual Search Task Paradigm. Diagram A represents a static view without a target present, Diagram B represents a static view of the break period, and Diagram C represents a static view with a target present. See the online article for the color version of this figure.

Equipment

MagStim DC stimulator. The transcranial DC stimulation (tDCS) was administered using a MagStim DC stimulator system (MagStim Company Limited; Whitland, U.K.). The device allowed for a continuous current (up to 5,000 μA) to be passed through the electrode configuration for a specified duration. In our current condition, we applied a 2mA current for a duration of 30 minutes. The MagStim DC stimulator was battery-powered and had built-in safety features to ensure the current was continuous and the impedance was within the allowable guidelines. If the impedance reached 50 kΩ, the DC stimulator would automatically shut down to reduce any risks of burns or electrical shock from occurring. Programming codes were provided to implement a double-blinded study. The programming code would either provide stimulation or sham conditions. In the sham condition the current ramped up to 2mA over a duration of 15 seconds then stayed constant for an additional 30 seconds after reaching 2mA. The current was then ramped down to zero over a duration of 15 seconds. In doing so, each participant in the sham scenarios was under the impression that they were receiving the brain stimulation during the study.

tDCS electrodes. In previous research studies (Coffman et al., 2012; Eun Kyoung & Nam-Jong, 2011; Hauser, Rotzer, Grabner, Mérillat, & Jäncke, 2013), wet sponge electrodes were used to administer the electrical current for tDCS. However, we used a custom design of silver/silver chloride electroencephalographic (EEG) electrode. The custom designed electrodes represented greater stability over time, produced lower sensations over time, and displayed less skin irritation when compared to wet sponge electrodes (Petree, Bullard, Jung, & Paulson, 2011). The electrode configuration consisted of a 5 EEG array electrode design. The electrical current was passed between two 3 cm $\times$ 5 cm (35 cm^2) conductive EEG electrodes. When 2mA was supplied from the MagStim DC stimulator, the average current density was 0.199 mA/cm^2.

Transcranial direct current stimulation (tDCS). Three various electrode configuration paradigms were implemented in the experimental design (anodal, cathodal and sham stimulation). When the participants received anodal stimulation, the anode electrode was placed over the left frontal eye field (LFEF). If the participant receives cathodal stimulation, the cathode electrode was placed over the LFEF (See Figure 2). The electrical current modifies the cortical excitability of the neurons, in turn altering the resting membrane potential. Anodal tDCS produced a transient increase in cortical excitability, whereas the cathodal stimulation caused a short-term reduction in cortical excitability (Hendy & Kidgell, 2013). Each of the participants performed three days of stimulation (anodal, cathodal, sham conditions), and the sequential order was randomized.

FaceLab. The eye-tracking system used in this study was FaceLab. FaceLab was a real-time off body eye tracking system that has the capability to record eye movement, blink frequency and duration, percent of eye closure (PERCLOS), and head positioning. The recorded eye metrics were analyzed and correlated in relation to the participant's performance during the task. The FaceLab system consisted of two cameras and an infrared source which are placed under the computer monitor. A sampling rate of 60Hz was employed during the recording of each participant's eye metrics. For FaceLab to effectively track the pupil, a distance of 32 in. from the nasion to the center of the screen was required.

Procedures

The study took place over four separate days. On day one, each of the participants was pro-

Figure 2. The tDCS electrode configuration over the left frontal eye field (LFEF) region of the scalp. See the online article for the color version of this figure.

vided with a verbal overview involving the contents and description of the study. If they wished to participate, each participant would sign an informed consent document (ICD) which stated the appropriate information and background involving noninvasive brain stimulation. An Initial Screening Questionnaire was provided to gather background information for eligibility. If the participants met the inclusion criteria, they were able to continue forward in the study. Following completion of the overview and forms, training on the task would begin. First, a 10-minute verbal feedback training session was performed. During this session, the participants would be provided with verbal feedback on their responses immediately following the visual search paradigm. If they responded correctly to the image, they would hear "Hit." If they responded incorrectly to the image, they would hear "False Alarm." Lastly, if the participant did not respond to the image, they would hear "Miss." After the 10-minute training session of the task, each participant would be provided with a short break before completing the main task session. The main task was similar to the training session, however the main task session was 30 minutes in duration and there was no verbal feedback on their response. Once the main task session was completed, each participant was able to leave for the day. It is important to note that there is no stimulation on day one; this day was strictly for training purposes. Moreover, days two, three, and four entailed providing noninvasive brain stimulation during the task in one of three conditions (anodal, cathodal or sham). Each of the participants experienced all three conditions, however the sequence of stimulation was randomized per participant.

Results

The results from the study were divided up into two separate sections: Accuracy and Eye Metrics. First, the accuracy section covers the analysis and results of the correctly detected targets for each treatment condition with respect to the time on the task. Second, the eye metrics section details the analysis of the blinking frequency and PERCLOS eye metrics for each treatment condition with respect to time on the task.

Analysis for Accuracy

To examine the effects of tDCS on visual search accuracy, an Analysis of Variance was conducted with factors Condition, Time, and the interaction of Condition and Time. The condition variable had three levels: sham, anodal, and cathodal stimulation. The time variable was defined as 10-minute intervals during the 30-minute task (0 to 10 min, 10 to 20 min, 20 to 30 min). The ANOVA did not reveal a significant main effect of condition, $F(2, 22) = 0.95$, $p = .4034$, or time, $F(2, 22) = 2.97$, $p = .0724$ on visual search accuracy. However, there was a significant interaction between condition and time, $F(4, 44) = 3.42$, $p = .016$ (see Table 1).

To examine the differences in means between the stimulation conditions at each time interval, a series of paired t tests was conducted (see Table 2). There was a statistically significant difference in accuracy between anodal and sham stimulation condition during the 10- to 20-minute time interval, $t = -2.84$, $p = .0161$. The change in performance from each time period to the following time period was then compared using a series of paired t tests. This was done to examine changes in performance over time for each of the three conditions. Table 3 displays the results. The sham stimulation condition shows a statistically significant change in accuracy from 0 to 10 minutes to the 10- to 20-minute time interval, $t = -2.35$, $p = .0383$, and from 0–10 minutes to the 20- to 30-minute time interval, $t = -3.29$, $p = .0072$. The mean accuracies for the sham condition were $M = 83.9$ ($SEM = 3.7$), $M = 78.0$ ($SEM = 2.5$), and $M = 77.4$ ($SEM = 2.2$) during the 0- to 10-min, 10- to 20-min, and 20- to 30-min time intervals, respectively. Additionally, the anodal condition exhibited a statistically significant change from 0–10 minutes to 10–20

Table 1
ANOVA Depicting the Relationship Between the Main Factors for the Accuracy Analysis

Source	*df*	*SS*	*dfe*	*SSe*	*F*	*p*
Condition	2	132	22	1538	.95	.4034
Time	2	235	22	872	2.97	.0724
Condition × Time	4	522	44	1676	3.42	.0160*

* Statistical significance at an alpha level of .05.

Table 2
Paired t Test Results Comparing the Conditions at Each Time Interval for the Accuracy Analysis

	Condition		Mean accuracy			Two-tailed paired t test		
Time	Level 1	Level 2	Level 1	Level 2	Mean diff.	n	t	p
0 to 10 min	Sham	Anodal	83.91	79.85	4.06	12	1.26	.2330
	Sham	Cathodal	83.91	82.36	1.55	12	.42	.6793
	Anodal	Cathodal	79.85	82.36	−2.51	12	−.84	.4215
10 to 20 min	Sham	Anodal	77.97	87.02	−9.05	12	−2.84	.0161*
	Sham	Cathodal	77.97	82.70	−4.74	12	−1.60	.1390
	Anodal	Cathodal	87.02	82.70	4.31	12	1.84	.0932
20 to 30 min	Sham	Anodal	77.35	80.13	−2.78	12	−1.43	.1808
	Sham	Cathodal	77.35	80.13	−2.78	12	−1.02	.3304
	Anodal	Cathodal	80.13	80.13	−.00	12	−.00	.9999

* Statistical significance at an alpha level of .05.

minutes, $t = 3.46$, $p = .0054$ and from 10–20 minutes to 20–30 minutes, $t = -2.43$, $p = .0334$. The mean accuracies for the anodal condition were $M = 79.9$ ($SEM = 2.9$), $M = 87.0$ ($SEM = 2.6$), and $M = 80.1$ ($SEM = 2.5$) during the 0- to 10-min, 10- to 20-min, and 20- to 30-min time intervals, respectively. Finally, the mean accuracies for the cathodal condition were $M = 82.4$ ($SEM = 1.5$), $M = 82.7$ ($SEM = 2.3$) and $M = 80.1$ ($SEM = 2.9$) during the 0- to 10-min, 10- to 20-min, and 20- to 30-min time intervals. Figure 3 provides a graphical representation of the accuracy means with respect to condition and time.

Analysis for Reaction Time

Just as in the accuracy analysis, RT was evaluated using an ANOVA with factors Condition, Time, and the interaction of Condition and Time. The F tests did not reveal statistically significant main effects of condition, $F(2, 22) = 1.54$, $p = .2373$, time, $F(2, 22) = 1.62$, $p = .2214$, or interaction of condition and time, $F(4, 22) = 0.45$, $p = .7705$, on the outcome variable (RT).

Analysis for Eye Metrics

It's important to note that a few participants were unable to have their pupils successfully tracked by the FaceLab system. For this reason, data from nine participants for the sham condition and eight participants for both the anodal and cathodal conditions were able to be evaluated and analyzed.

Similar to the visual search accuracy analysis, blinking frequency and PERCLOS were evaluated using an ANOVA with factors Con-

Table 3
Paired t Test Results Comparing the Significance of Change From One Time Interval to a Following Time Interval for the Accuracy Analysis

		Accuracy		Two-tailed paired t test		
Condition	Time change	Mean change	*SEM* change	n	t	p
Sham	First to second	−5.94	2.53	12	−2.35	.0383*
	First to third	−6.56	1.99	12	−3.29	.0072*
	Second to third	−.61	1.72	12	−.36	.7282
Anodal	First to second	7.16	2.07	12	3.46	.0054*
	First to third	.28	2.24	12	.12	.9040
	Second to third	−6.89	2.83	12	−2.43	.0334*
Cathodal	First to second	.34	2.23	12	.15	.8817
	First to third	−2.23	3.08	12	−.72	.4840
	Second to third	−2.57	3.57	12	−.72	.4868

* Statistical significance at an alpha level of .05.

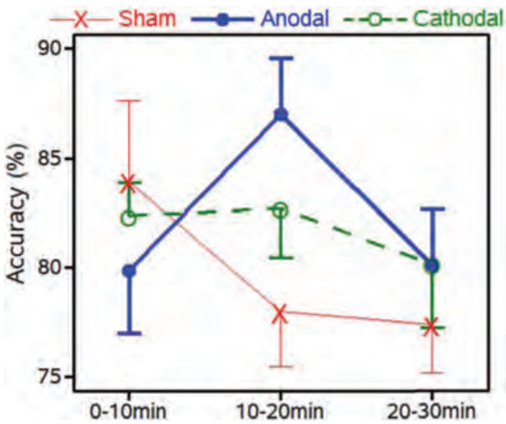

Figure 3. Accuracy plot associated with each of the three conditions with respect to the 10-minute time intervals. See the online article for the color version of this figure.

dition, Time, and the interaction of Condition and Time. The results are presented in Table 4. There was no significant main effect of time on blinking frequency, $F(2, 16) = 0.36$, $p = .7054$. In addition, the interaction between condition and time failed to achieve statistical significance, $F(4, 31) = 2.36$, $p = .0752$ for blinking frequency. However, there was a significant main effect of stimulation condition on blinking frequency, $F(2, 15) = 6.66$, $p = .0083$. As seen in Table 4, there was no significant effect of time on PERCLOS, $F(2, 16) = 0.34$, $p = .7192$. There was, however, a significant main effect of condition, $F(2, 15) = 5.71$, $p = .0140$, and a significant interaction between condition and time, $F(4, 31) = 2.92$, $p = 0.0369$, on PERCLOS.

Table 5 displays two-tailed paired *t* tests comparing the conditions at each time interval for blinking frequency and PERCLOS. There was a significant difference in blinking frequency between anodal and sham condition, $t = -4.49$, $p = .0020$, and between anodal and cathodal condition, $t = 3.23$, $p = .0145$, during the 0- to 10-minute time interval. Additionally, there was a significant difference in blinking frequency between the anodal and sham condition, $t = -3.20$, $p = .0126$, and between anodal and cathodal condition, $t = 3.15$, $p = .0161$, during the 10- to 20-minute time interval. Mean blinking frequencies for the anodal condition were $M = 17.6$ ($SEM = 1.5$), $M = 17.9$ ($SEM = 2.0$), and $M = 16.2$ ($SEM = 2.2$) during the 0- to 10-min, 10- to 20-min, and 20- to 30-min time intervals, respectively. The mean blinking frequencies for cathodal stimulation were $M = 11.6$ ($SEM = 1.5$), $M = 12.3$ ($SEM = 2.4$), and $M = 13.8$ ($SEM = 1.9$) during the 0- to 10-min, 10- to 20-min, and 20- to 30-min time intervals. For sham stimulation, the mean blinking frequencies were $M = 12.3$ ($SEM = 1.3$), $M = 11.9$ ($SEM = 1.9$), and $M = 13.9$ ($SEM = 2.3$) during the 0- to 10-min, 10- to 20-min, and 20- to 30-min time intervals, respectively.

Our analyses also revealed a significant main effect of condition on PERCLOS, $F(2, 15) = 5.71$, $p = .0140$, and a significant interaction between condition and time, $F(4, 30) = 2.92$, $p = .0369$, with respect to PERCLOS. The PERCLOS means were $M = 5.5$ ($SEM = 0.5$), $M = 5.7$ ($SEM = 0.6$), and $M = 5.0$ ($SEM = 0.6$) during the 0- to 10-min, 10- to 20-min, and 20- to 30-min time intervals for anodal stimulation. For cathodal stimulation, the PERCLOS means were $M = 3.6$ ($SEM = 0.4$), $M = 3.9$ ($SEM = 0.7$), and $M = 4.4$

Table 4
ANOVA Depicting the Relationship Between the Main Factors for the Eye Metric Data

Dependent variable	Source	*df*	*dfe*	*F*	*p*
Blink frequency	Condition	2	15.2	6.66	.0083*
	Time	2	16.1	.36	.7054
	Condition × Time	4	30.7	2.36	.0752
PERCLOS	Condition	2	15.3	5.71	.0140*
	Time	2	16.2	.34	.7192
	Condition × Time	4	30.8	2.92	.0369*

* Statistical significance at an alpha level of .05.

Table 5
Paired t Test Results Comparing the Conditions at Each Time Interval for the Blinking Frequency and PERCLOS

Dependent variable	Time	Condition		Mean			Two-tailed paired *t* test		
		Level 1	Level 2	Level 1	Level 2	Mean diff.	*n*	*t*	*p*
Blink frequency (blinks/min)	0 to 10 min	Sham	Anodal	12.3	17.6	−5.3	9	−4.49	.0020*
		Sham	Cathodal	12.7	11.8	.9	8	.42	.6841
		Anodal	Cathodal	17.8	11.8	5.9	8	3.23	.0145*
	10 to 20 min	Sham	Anodal	11.9	17.9	−5.9	9	−3.20	.0126*
		Sham	Cathodal	11.9	12.5	−.6	8	−.27	.7977
		Anodal	Cathodal	18.3	12.5	5.9	8	3.15	.0161*
	20 to 30 min	Sham	Anodal	13.9	16.2	−2.3	9	−1.47	.1802
		Sham	Cathodal	13.5	13.8	−.3	8	−.20	.8504
		Anodal	Cathodal	16.4	13.8	2.6	8	1.80	.1150
PERCLOS	0 to 10 min	Sham	Anodal	3.7	5.5	−1.8	9	−4.85	.0013*
		Sham	Cathodal	3.9	3.7	.2	8	.29	.7797
		Anodal	Cathodal	5.6	3.7	1.9	8	2.80	.0264*
	10 to 20 min	Sham	Anodal	3.7	5.7	−2.0	9	−3.10	.0147*
		Sham	Cathodal	3.7	4.0	−.3	8	−.49	.6373
		Anodal	Cathodal	5.9	4.0	1.9	8	2.52	.0397*
	20 to 30 min	Sham	Anodal	4.2	5.0	−.8	9	−1.62	.1430
		Sham	Cathodal	4.1	4.4	−.3	8	−.76	.4727
		Anodal	Cathodal	5.1	4.4	.7	8	1.12	.3016

*Statistical significance at an alpha level of .05.

(*SEM* = 0.6) during the 0- to 10-min, 10- to 20-min, and 20- to 30-min time intervals. Finally, the PERCLOS means for sham stimulation were *M* = 3.7 (*SEM* = 0.4), *M* = 3.7 (*SEM* = 0.5), and *M* = 4.2 (*SEM* = 0.6) during the 0- to 10-min, 10- to 20-min, and 20- to 30-min time intervals, respectively. Paired *t* tests revealed a significant difference in PERCLOS between the anodal and sham condition, $t = -4.85$, $p = .0013$, and between the anodal and cathodal condition, $t = 2.80$, $p = .0264$, during the 0- to 10-minute time interval. Further, there was a significant difference in PERCLOS between the anodal and sham condition, $t = -3.10$, $p = .0147$, and between the anodal and cathodal condition, $t = 2.52$, $p = .0397$, during the 10- to 20-minute time interval. The blinking frequency means are displayed in Figure 4, and the PERCLOS means are depicted in Figure 5 for each condition and time interval.

Discussion

Similar to the results section, the discussion was segregated into two separate sections for the performance and eye metric variables.

Accuracy

The ability to locate and detect targets among distractors quickly and efficiently is instrumental within a variety of tasks in the Air Force. As operators move toward supervisory tasks, critical targets or pieces of information are often

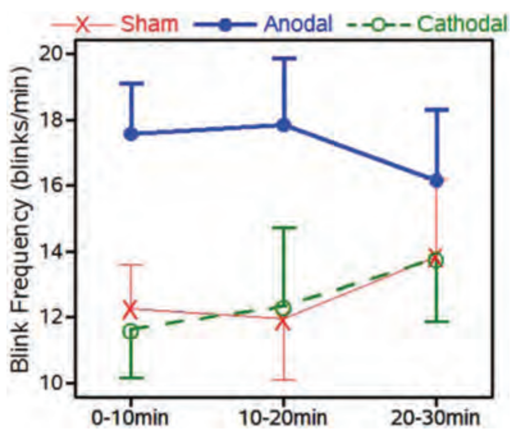

Figure 4. Blinking frequency plot associated with each of the three conditions with respect to the 10-minute time intervals. See the online article for the color version of this figure.

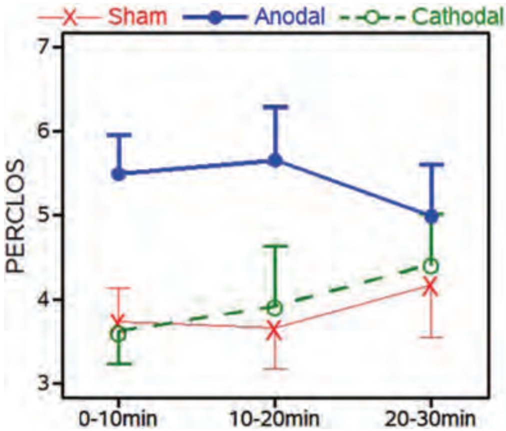

Figure 5. PERCLOS plot associated with each of the three conditions with respect to the 10-minute time intervals. See the online article for the color version of this figure.

infrequent. With infrequent targets, performance tends to decline as the time on the task increases (i.e., the vigilance decrement (Lara, Madrid, & Correa, 2014; Wiggins, 2011; McIntire et al., 2013)). This performance decline is primarily in the form of decreased target detection which may result in serious repercussions. In this study, our objective was to examine the effects of transcranial DC stimulation over the left frontal eye field region to improve visual search and detection accuracy.

Our results have shown that anodal and cathodal stimulation applied to a scalp location over the LFEF provides an improvement in detection accuracy compared to the sham stimulation condition. Importantly, this effect varies with time. Our data suggest the effect is strongest in the second 10 minutes of the task. Specifically, anodal stimulation only exhibited a significant improvement in target detection accuracy of approximately 8% over the sham condition during the 10- to 20-minute time interval. It is notable that the anodal group's accuracy significantly improved by approximately 8% from the 0–10 to 10–20 minute time interval, whereas the sham group's mean significantly declined by about 6%. This improvement was temporary, as the detection rate returned to approximately baseline levels in the 20–30 minute time segment. It is interesting to note that this temporary improvement was also reported in Nelson et al. (2014) and McIntire et al. (2014). Although the exact mechanisms causing this temporary improvement are currently unknown, it may be attributable to short-lived increases in brain activation that led to an increase in processing power to the affected regions (Brem et al., 2014). The longer effect of simply preserving vigilance (rather than improving vigilance) may be attributable to long lasting long-term potentiation-like effects on plasticity within neural networks engaged in executing this cognitive task (McIntire et al., 2014). It is not known whether changing the duty cycle or "cycling" the tDCS would create a longer lasting vigilance enhancement. Although there were no significant differences in accuracy across the stimulation conditions for the 20–30 minute interval, it should be noted that the performance during sham stimulation significantly declined over the 30-minute task (i.e., there was a measureable vigilance decrement), whereas the accuracy in the anodal stimulation group did not. Hence, although there were no significant differences in the means during the final time interval, the data does support the idea that tDCS prevented a decline in performance attributable to time on task. This may not have been detected because we were unable to compare the means across the data as a result of the data not being normalized to the baseline. Any possible effect of treatment condition on accuracy may have been partially masked by a small, but not statistically significant difference in initial performance (i.e., 10–20 minute interval). In future studies, we suggest baseline performance is measured before the initiation of the stimulation. The data can then be normalized to the baseline to examine the extent to which tDCS influences changes in performance rather than the absolute means.

Although there were no statistically significant differences in mean target detection accuracy between sham and cathodal stimulation, performance over time did not significantly alter. Specifically, there were no significant differences in any of the comparisons between the 3 times points. These data provide insight that when providing anodal and cathodal stimulation over the LFEF, visual search performance increases or remains consistent during the 30-minute task. Hence, the vigilance decrement is mitigated. As previously noted, the performance is conditioned to significantly decline at each time point, demonstrating a time on task effect (i.e., vigilance decrement). Hence, Figure 3 suggests that both anodal and cathodal tDCS eliminated the overall performance decline over time. Temporary yet significant improvements in target detection accuracy were also exhibited only with anodal stimulation in the second 10 minutes of the task.

Importantly, these results are nearly identical to the findings from our first examination of the effects of tDCS on vigilance performance (Nelson et al., 2014). Although the duration of the task was longer in our original study (40 minutes vs. 30 minutes) and the tasks differed, the anodal stimulation exhibited the same temporary improvement in target detection accuracy that dissipated in the next 10-minute interval. Further, our original study showed that both anodal and cathodal tDCS prevented the decline in performance over time, just as in the study described herein. One important difference between the studies was that the original study (Nelson et al., 2014) included a baseline measure of performance that was then used to convert the data into a percentage change from the baseline to normalize the data, whereas our current study did not. Because performance may differ across days as a result of a variety of factors such as time of day, level of fatigue, stress, and so forth, normalizing the data reduces the influence of these factors and provides a clearer indication of differences in trends over time. As a result, we were able to determine the performance effects in relation to each condition's absolute means. Another interesting point is that tDCS was applied bilaterally to F3/F4 the original experiment, whereas here we used LFEF with the reference electrode applied to the contralateral bicep. The scalp locations are relatively close to each other and the electrodes provide a relatively large and diffuse area electrical field potential within the brain (Datta et al., 2009). Hence, this may provide initial evidence that the effect on vigilance is not overly sensitive to precise electrode placements on the scalp or a particular electrode montage. Furthermore, the effect appears to not be task specific, provided that the task utilized tests the same cognitive skill.

Our study did not find any changes in RT with respect to factors Condition, Time, and the interaction of Condition and Time. A study using another form of noninvasive brain stimulation called transcranial magnetic stimulation (TMS) was also unable to find changes in RTs that were likely due to ceiling effects (Nelson et al., 2014). Because the task included a limited time window to search each image, we believe ceiling effect is also the cause of this finding in our study.

Eye Metrics

Previous research has shown that a variety of eye metrics such as percent of eye closure (PERCLOS) and blinking frequency are correlated with an individual's vigilance performance level (McIntire et al., 2013). In our current study, we evaluated both PERCLOS and blinking frequency to determine if such trends existed in our testing paradigm.

The FaceLab software was implemented to record the pupils of each participant during the task. From the information collected, the blinking frequency and PERCLOS data were analyzed. The blinking frequency represented in Figure 4 shows that when participants received anodal stimulation, their blinking frequencies were significantly higher compared with the cathodal and sham conditions. Because anodal stimulation yielded significant improvements in performance and prevented a measurable vigilance decrement, it appears the increased blink frequency may be associated with improved performance (i.e., higher and more consistent target detection accuracy). Our data support a previous finding by Caffier (Caffier, Erdmann, & Ullsperger, 2003). They concluded that when performing a mental search task, an increase in blinking frequency was correlated with an alert mental state whereas a decrease in blinking frequency was correlated to a drowsy mental state (Datta et al., 2009). Additionally, high workload visual search tasks require continuous eye movement, and these eye movements are often associated with eyeblinks. For example, Tsai, Viirre, Strychacz, Chase, and Jung (2007) found that blink frequency increased during a visually demanding driving task but not for a simpler version of the task. The theory is that the saccade is embedded in the eyeblink itself. Hence, each blink coincides with eye movement to a new region of interest. Given the difficulty of the task and the time stress of searching the image, it is possible that the increased blink frequency detected with anodal stimulation was caused by an increased scan rate, with each blink indicating a new eye movement to a different section of the screen. Moreover, participants with a higher blinking frequency displayed a higher target detection performance.

The data also suggest that tDCS has an effect on PERCLOS. The results show that anodal stimulation exhibited the largest PERCLOS over the duration of the task. PERCLOS has been previously correlated with the vigilance decrement, where lower vigilance performance was associated with larger PERCLOS measurements. However, the anodal stimulation condition also exhibited a higher blink rate when compared with sham or cathodal tDCS. PERCLOS measures the total amount of time the eyes are closed over a specified period and described this closure as a percentage of the total time. Because the eyes close during each blink, the blinks can influence the total amount of time the eyes are closed. Hence, this very small yet significant difference in PERCLOS may have simply been caused by the increased blink frequency. Of note, a previous study revealed that a missed response seldom occurred when the PERCLOS value was less than 11.5% (Abe et al., 2011). Because the observed PERCLOS values were very small (i.e., under 10%), it is unlikely that the increased PERCLOS had any impact on the performance outcomes.

Conclusion

The current study evaluated the efficacy of transcranial DC stimulation (tDCS) to augment human performance during a visual search task. Our results indicated that the use of anodal and cathodal tDCS over the LFEF improves target detection accuracy during a visual search task. A significant difference was observed between the anodal and sham conditions for the 10-to 20-min time interval showing a 9% difference in target detection. Additionally, both the anodal and cathodal conditions prevented a significant decline in performance caused by time on task. This finding is important to note because the vigilance decrement was dramatic for the sham condition across the duration of the task. These results are analogous to our previous work that provided initial evidence tDCS can mitigate the vigilance decrement, even though the task, stimulation duration, and electrode placement varied between the two experiments. The results suggest that the effects on vigilance are repeatable, and the short-term effects are relatively insensitive to small changes in electrode position, electrode montage, and the performance task utilized.

The eye metrics parameters that were evaluated (Blinking Frequency and PERCLOS) showed mixed results. Blinking frequency was significantly elevated during anodal tDCS of the LFEF, suggesting a higher visual search activity. Conversely, the PERCLOS was very small across the duration of the task and did not yield any insights into the performance of the participants. This conflicts with previous work showing a relationship between eye metrics and vigilance performance. It is possible that other eye metrics not examined here would yield such relationships.

Future research should examine the longevity of the effect of noninvasive brain stimulation on vigilance. It was observed in this study that the performance for the participants that received anodal and cathodal stimulation remained level or improved during the 30-minute task. However, could this cognitive improvement continue past the 30-minute task? A study conducted by McIntire (McIntire et al., 2014) provided evidence which showed that 30 minutes of tDCS at 2mA had a cognitive benefit that lastly the duration of the study, roughly six hours. The next phase would be to determine the longevity of the effect of noninvasive brain stimulation on vigilance, which has yet to be accomplished.

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