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Using Transcranial Direct Current Stimulation (tDCS) to Modulate Performance during a Multimodal Auditory and Visual Vigilance Task

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Abstract

Detecting infrequent, low-salience targets is a critical task in many mentally fatiguing jobs, such as sonar monitoring. Vigilance is necessary for optimal performance on these tasks, as watch shifts can last several hours. The ability to maintain attention over time, i.e. vigilance, can degrade in as little as ten minutes. This decrement is often attributed to limited cognitive resources and the subsequent mental fatigue, and manifests as increased target misses and longer reaction times. Transcranial direct current stimulation (tDCS) may serve as a countermeasure to vigilance decrement. Research shows that tDCS to the dorsolateral prefrontal cortex (DLPFC) can be used to improve performance on visually-based vigilance tasks, but the use of tDCS for auditory or multisensory (visual and auditory) vigilance tasks has been underexplored. We investigated the effectiveness of tDCS to the DLPFC for improving vigilance on visual-only, auditory-only, and multimodal auditory-visual vigilance tasks. Results indicate that anodal tDCS improved visual response times, but stimulation also decreased auditory sensitivity and specificity. For the multimodal auditory-visual vigilance task, the effects of anodal tDCS were not significantly different from sham tDCS, revealing differential effects of anodal tDCS on varying task modalities and outcome measures.

Keywords: transcranial direct current stimulation (tDCS), vigilance, sustained attention, cognitive fatigue, audiovisual

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Introduction

Selective attention to important threats and targets in the environment is critical to the survival of any mammal. Unfortunately, our surroundings offer too much information for us to process at once; therefore, incoming sensory inputs are filtered. Through this filter we attend only to a subset (i.e., survival-relevant) of stimuli through a combination of bottom-up, stimulus-driven attention, and top-down, goal-directed attention.[1] Whereas bottom-up attention is nearly automatic, as it is captured by a salient stimulus (such as when a loud noise occurs), top-down attention requires memory and sometimes additional effort (such as when searching for a familiar face within a crowd).[1] Attention can be directed toward stimuli within a single sensory modality, such as when listening to music, or it can be split (via rapid switching) between multiple modalities, such as when reading a book while listening to a conversation. When top-down attention is divided between two tasks of different modalities, performance on one or both tasks may decline due to excess demands on cognitive resources.[2-4]

Divided attention is an important area of study in human cognition because of its implications for public safety. For instance, "distracted driving" and the demand for novel methods to augment cognition to supernormal levels so that critical societal tasks that unavoidably require divided attention (e.g., emergency response, national defense) can be executed optimally. Despite the importance of this area of study, relatively little is known about how divided attention is affected by time on task—a key knowledge gap considering the extended durations and vigilance required for the performance of most tasks. Vigilance is the ability to sustain goal-directed attention over long periods of time.[5,6] Vigilance is essential to most tasks and jobs in the modern world, including driving a vehicle, sonar monitoring, security scanning, and satellite image surveillance. Maintaining vigilance requires allocating sufficient amounts of cognitive resources (i.e., blood flow and oxygenation) to the relevant brain regions during performance of a long duration and/or tedious task. This ability declines in as little as ten minutes, resulting in slowed reaction times and/or missed targets, i.e., the vigilance decrement.[6,7] Maintaining vigilance for extended periods of time, or across divided attention, depletes the allocated cognitive resources, as reflected by decreased blood flow and oxygenation measured by positron emission tomography and functional near-infrared spectroscopy.[8,9]

Vigilance maintenance requires high levels of executive functioning, which includes top-down attention, goal maintenance, and effective filtering of irrelevant information, each of which is cognitively taxing.[10-12] Top-down attention is important to detect weak or difficult to perceive target signals, goal maintenance prevents distraction or interference of task-extraneous thoughts, and filtering irrelevant information helps boost the signal-to-noise ratio and attend only to relevant information.[13] The dorsolateral prefrontal cortex (DLPFC) mediates each of these functions;[13] therefore, if cognitive resources could be maintained in the DLPFC, theoretically, the vigilance decrement could be minimized. Researchers have used transcranial direct current stimulation (tDCS) on the DLPFC to modulate cortical activation and increase blood flow and oxygenation in the stimulated region, demonstrating that such an intervention may be effective in reducing the vigilance decrement.[14-17]

tDCS is a method of stimulating the cerebral cortex with small electrical currents. Though the precise mechanism through which tDCS influences behavior is unknown, behavioral and physiological evidence indicate that at the simulated site, tDCS modulates a cell's resting membrane potential.[18,19] This transient change in the excitability of the resting membrane potential may impact synaptic communications within a brain network with functional consequences. Within the visual modality, anodal stimulation—stimulation in which neuronal excitability is increased—to frontal brain regions demonstrated facilitatory effects to perceptual learning and improving visual search accuracy.[20] However, not all studies have found performance improvements. In a study using a similar montage (anodal stimulation to frontal brain regions, cathodal stimulation to the bicep), inhibitory effects in facial recognition accuracy were reported.[21] Despite these conflicting results, the research has generally shown benefits of tDCS on cognition with enhancements in performance[22-24] and sustained attention[8,25,26] that extends to audition.[27,28] Furthermore, neuroimaging techniques used in conjunction with tDCS indicate that tDCS can increase blood flow and oxygenation to the stimulated region–resources hypothesized to be depleted by prolonged, effortful vigilance.[6,29,30] It has been posited that this increase is mediated by neuronal and/or astrocyte activity.[16] Given the proposed mechanisms of performance improvement through tDCS (increased resources), and the performance-inhibiting vigilance decrement (a lack of resources), tDCS may be an effective tool to reduce the vigilance decrement.

Specifically, using tDCS to increase cognitive resources to the DLPFC, a region where cognitive resources are often depleted as a result of the vigilance decrement, may improve vigilance-based performance. Though limited, there has been some work investigating the effects of tDCS on vigilance. In these studies, participants performed a visual vigilance task requiring the detection of infrequent targets amongst non-critical stimuli. The sham stimulation groups showed the standard vigilance decrement: a slowed and/or reduced target detection rate over time. The group receiving anodal stimulation to the DLPFC, however, performed significantly better, with reaction times decreased, relative to the control group.[14,31,32] These studies reported a dramatic, five-fold improvement in vigilance, and attributed this to increased cognitive resources, allowing the participants to remain vigilant for longer periods of time.[7,32]

Despite previous work indicating that tDCS can improve performance in visual vigilance tasks, researchers have not yet fully investigated whether tDCS can improve auditory vigilance or multisensory visual and auditory vigilance. In theory, tDCS of the DLPFC should similarly benefit auditory vigilance tasks, as both modalities rely on the same brain region for sustained attention, but this remains to be demonstrated.[7,33,34] It may also be more difficult to predict how tDCS would impact multisensory vigilance-based performance. Dividing attention by responding to symbolic/abstract auditory and visual stimuli within the same task results in a decrease in performance, even without the deleterious effects of the vigilance decrement;[2-4] this decrease is further exacerbated when an observer must divide attention across two types of stimuli in a vigilance task.[35] Both forms of performance decrements—multisensory monitoring and vigilance—are attributed to a lack of resources (blood flow and oxygenation), which tDCS is capable of increasing. However, it is unknown if tDCS can increase cognitive resources sufficiently to alleviate the decrements associated with monitoring two modalities of information for long periods of time. Prior research has shown no significant effects of anodal stimulation over the DLPFC on dual-task performance in which auditory and visual stimuli occurred simultaneously.[36] From a capacity-sharing perspective, tDCS was not able to increase the capacity of available resources to overcome the cost of performing the secondary task.

The current study investigated the effects of tDCS administration on visual, auditory, and multimodal task performance, for which we predict: 1) tDCS will improve visual vigilance, in a replication of previous work; 2) tDCS administration will also improve auditory vigilance, given that auditory vigilance relies on the same DLPFC-based resources as visual vigilance; and 3) tDCS will be unable to meet the full cognitive resource demands (blood flow/oxygenation) of multimodality monitoring combined with the cognitive resource demands of vigilance, resulting in reduced multimodal vigilance task performance in comparison to single-modality vigilance task performance. To examine these hypotheses, vigilance-based performance was evaluated in groups divided by task and stimulation type. Participants completed the same type of vigilance task, either a visual-only, an auditory-only, or a multimodal (visual and auditory) vigilance task, on two separate days. While performing the task, participants received a type of stimulation (either anodal or sham) to the DLPFC, receiving the other type of stimulation on the second day. The vigilance decrement predicts that performance for all groups will decline over time; however, receiving anodal stimulation may be able to overcome the vigilance decrement through increased cognitive resources via tDCS.

Method

Participants.

Twenty participants comprised the study sample. Recruitment was open and opportunistic and did not target any specific Navy command or population. A minimum required sample size estimation calculated using G*Power 3.1[37] for an analysis of variance repeated measures, within-between interaction (alpha = 0.05; power (1-β) = .80, f (large effect size) = 0.35, number of groups = 2, number of measurements = 6) yielded a minimum sample size of 12. With the current study's design, an additional 6 samples were added for the second modality comparison (i.e., audition and vision). Prior literature[15] comparing vigilance-based target misses between anodal and sham stimulation groups resulted in a large effect size (patrial $\eta^2 = 0.2$, f = 0.50). The sample size estimates are also comparable to tDCS studies that have reported between 8-12 participants per group.[8,14,17,20,25,38]

All participants completed a self-reported screening questionnaire that determined their eligibility for the study, signed informed consent, and received monetary compensation ($20/hour). To be eligible, participants had to report normal or corrected-to-normal hearing and vision, normal motor coordination, be right-handed, and be between the ages of 18-65 years. Participants were screened for tattoos around the left arm and/or head, and for receiving shots in the left arm within the past 30 days to ensure that tDCS electrode placement would not increase risk or injury to the participant from infection or other skin complications. All participants were excluded for self-reported neurological or psychological diagnosis; psychological hospitalization; recent hospitalization for surgery/illness within the past 30 days; psychotropic medications use, including the use of tobacco; drug or alcohol treatment in the past six months; non-removable metal or cardiac pacemaker or brain stimulator; implanted intracranial metals; or implantable birth control devices. Participants who were pregnant, could be pregnant, or who gave birth within the past 6 months were also excluded.

Two participants were excluded from analyses for having satisfied one or more items from the exclusionary criteria. These participants signed consent, but during the review of the screening questionnaire were found to be ineligible and no further data were collected. The final sample consisted of 18 participants that were included in the data analysis. Of the remaining participants 6 were female (33%) and 12 were male (67%), between 21 and 48 years-old with a mean age of 29.22 years (SD = 8.27). All procedures were approved by the Naval Submarine Medical Research Laboratory (NSMRL) Institutional Review Board (IRB).

Questionnaires.

In addition to the screening questionnaire given prior to the start of the first testing session, participants also completed a demographics questionnaire and a sensation questionnaire (see **Supplemental Figure 1**). Additional questions captured participants' music experience, sleep, and caffeine intake. The music experience questionnaire used a four-point scale with 1 indicating "novice" level and 4 indicating "expert" level. Caffeine use (prior to experiment), hours of sleep the night before each session, and mood before each session were all self-reported. A sensation questionnaire to gauge participants' response to tDCS was given at the start of tDCS and following four minutes of stimulation, on each testing session. Participants reporting adverse sensations (i.e., itching, pain, heat, or discomfort) as unbearable (a score of 9 or greater on a 10-point scale), would be removed from the study. At the end of each testing session, participants completed the NASA Task Load Index (NASA-TLX),[39] rating their perceived workload on the vigilance task.

Experimental task.

Participants completed a variation of the Integrated Visual and Auditory Continuous Performance Test (IVA-CPT),[40] reported previously[35] to assess vigilance on both session days. This test has been shown to be reliable and yield minimal practice effects.[41] The IVA-CPT is intended to be monotonous in order to mimic real-world vigilance tasks and to induce commission errors (false alarms), omission errors (misses), and slowed responses, all of which are indicative of the vigilance decrement. The task required participants to monitor for a target mixed with distractor presentations for approximately 52 minutes.

Stimuli consisted of lowercase characters from the Latin alphabet "p" and "b," with an ascender/descender length of 5 pixels (**Figure 1A**) in the Visual-only and Multimodal conditions, and auditory clips of the phonemes /p/ and /b/ with Gaussian noise measured at -16 decibels (dB) in the Auditory-only and Multimodal conditions. These stimuli parameters were previously demonstrated to be equally discriminable across modalities, with a performance threshold of 80% target identification accuracy.[35] Depending on the participant's assigned vigilance task condition, the stimuli were either visual, auditory, or both. Participants were instructed to respond to a target stimulus and to withhold a response to a non-target stimulus. The target was counterbalanced across participants between the letter/phoneme "p" and "b." The target to non-target ratio was 1:5.25. This resulted in 240 target trials and 1,260 non-target trails. In the Multimodal Auditory+Visual condition the ratio between auditory and visual trials was 1:1, and equated the number of target and non-target trials for both stimulus types. The stimulus presentation was randomized such that for every 250 trials the targets appeared on 40 trials and non-targets on 210, resulting in six blocks (Blocks I-VI).

The vigilance task was performed on a 15.6" monitor laptop with stimulus timing and data recording controlled using E-Prime 3.0 software (Psychology Software Tools Inc., Pittsburgh, PA, USA). Participants used their dominant (right) hand to make a response using a Chronos response box (Psychology Software Tools Inc, Pittsburg, PA, USA). On each trial a single stimulus was presented. The display background was white and appearing at the center of the screen was a white square outlined in gray that served as a fixation point and remained on screen for the duration of the task (**Figure 1B**). The speaker volume was set to the maximum (100%) with participants sitting centered in front of the computer approximately 65-70 cm from the screen. Stimuli were presented sequentially with a fixed trial length of 2,000 ms. The letters appeared at the center of the fixation box and were visible for 167 ms from the start of the trial.

The auditory stimuli were presented for 500 ms. The participants were allotted the entire trial time (2,000 ms) to make a response to a stimulus.

Transcranial direct current stimulation (tDCS).

The equipment used to administer tDCS stimulation was the neuroConn DC-Stimulator Plus, Transcranial Stimulator™ (neuroCare Group GmbH, Munchen, Germany). The neuroConn DC-Stimulator Plus delivered 2mA of stimulation for both stimulation conditions (anodal and sham). During the anodal condition participants received 2mA of stimulation for 30-minutes, whereas stimulation during the sham condition only lasted 30-seconds, with a ramp up to 2mA and a ramp down to zero to imitate real stimulation.[8,20] The sham stimulation controlled for placebo effects by minimizing the participants' ability to guess the type of stimulation they were receiving.[42] This method has reliably shown to blind participants.[43] The neuroConn device also indicated impedance level, and had a safety feature to shut off automatically if the impedance level exceeded 20 V.

The area of interest receiving stimulation via the anodal electrode was the right DLPFC which corresponded to the F4 scalp site according to the standard 10-20 system of electrode placement. The cathodal electrode was placed on the participant's left bicep.[20,44,45] To accommodate two participants with tattoos on the bicep the cathode electrode was placed lower on the left side. Custom electrode arrays (The Mind Research Network 2011) were used to deliver stimulation. Both the anode and cathode electrode arrays had five electroencephalography (EEG) electrodes in a circular configuration. This custom design utilized silver/silver chloride EEG electrodes instead of the standard wet sponge tDCS electrodes because research has shown improved current distribution, which reduces sensations and negative skin reactions associated with stimulation.[46] The arrangement of the custom electrodes had the five EEG electrodes spaced 0.75 cm from the center, 0.1 cm apart from a bordering electrode, and measuring 1.6 cm each in diameter. Conductive gel was applied at each electrode array site and within each electrode to ensure connectivity, and the electrodes were held in-place with medical bandages.

Procedure.

Testing took place across two separate days for each participant. The task condition and target stimuli (Auditory-only, Visual-only, Multimodal) were the same across both sessions for each participant. The sham and anodal stimulation was counterbalanced and double-blind across sessions. The sessions were separated by a minimum of 24-hours to avoid carryover tDCS effects influencing the participants' vigilance performance.[47] The perturbations of underlying neural dynamics from tDCS persists beyond the stimulation period.[48] Measures of evoked potentials in humans at 2 mA for 20-minutes have been shown to exhibit changes from baseline that last until the next morning.[49] There are reports of 30-minutes of tDCS lasting up to 6-hours post-stimulation before behavior was comparable to a control condition.[14] The average number of days between sessions was 6.72 (SD = 3.36 days).

Once participants were set-up with the tDCS device, they were seated in front of the laptop and response box. At the start of stimulation participants completed the sensation questionnaire. The sensation questionnaire was repeated after four minutes. During the four minutes of initial stimulation, instructions on how to complete the vigilance task were displayed on the laptop screen in each task condition. The instructions stated, "You will be using the device next to the computer to make your responses. You will hear or see (on the screen) the letter "b" or “p.” If you hear or see the letter “b” press the first button on the device. If you hear or see the letter “p” do not respond.” Depending on the participant’s assigned task condition (Auditory-only, Visual-only, or Multimodal), the instructions specified if the stimulus targets and non-targets were visual, auditory, or both. Additionally, the instructions distinguished which of the stimuli (the “b” or the “p”) was the target and which was the non-target. Participants were given both sample images and audio clips of the “b” and “p” before completing a short practice assessment. The practice assessment simulated the participant’s vigilance task, and consisted of ten trials in which participants indicated the presence of their assigned target, within their assigned task condition. After completing the practice and answering the sensation questionnaire for the second time, participants began the full vigilance task, which lasted approximately 50 minutes. Upon completion of the task, participants filled out the NASA-TLX. Participants were examined for any injury at the stimulation sites and were dismissed for the day. To control for potential time of day effects, participants returned for their second session that was scheduled during same time of day as the first session, and completed the same vigilance task but received the other type of stimulation.

Statistical analysis.

Three measures were used to evaluate performance on the vigilance task: specificity (true positive/all positives [TP/AP], hits), sensitivity (true negative/all negatives [TN/AN], correct rejections), and true positive reaction time. This study used a linear mixed model design with fixed effects of Condition (single-1 modality, multimodal-2 modality), Stimulation Type (anodal, sham), and Block (I-VI), with random effects of Session (first, second) and Participant. Independent analyses were applied for each dependent measure and each modality (Audition: Auditory-only and Multimodal auditory performance; Vision: Visual-only and Multimodal visual performance) and were not corrected for multiple comparison across the number of dependent measures.

The vigilance decrement would predict that scores would decrease over time (Blocks I-VI). If anodal tDCS increases cognitive resources for the single modality vigilance tasks, mitigating the vigilance decrement, then the results would indicate a significant 3-way interaction among Condition×Stimulation Type×Block. If the number of modalities the participant must monitor does not affect resource demands and tDCS improves performance across conditions, a Stimulation Type×Block interaction is anticipated. A Condition×Block interaction would indicate that anodal and sham tDCS had similar effects, but performance based on the vigilance task (single, multimodal) being different across blocks. Moreover, a significant Block effect would suggest that the vigilance decrement occurs whether or not the task is monitoring a single or multiple modalities and whether or not the participant is receiving anodal or sham tDCS.

To gauge tDCS effects on the subjective experience of performing the vigilance task, workload questionnaire (NASA-TLX) ratings were compared across sham and anodal stimulations.

Significant interaction effects were followed-up with a post-hoc test using pairwise comparisons with Bonferroni correction. Analyses were conducted using SPSS version 23 (IBM Corp) and R with an α level $p = .05$ with 2-tailed testing.

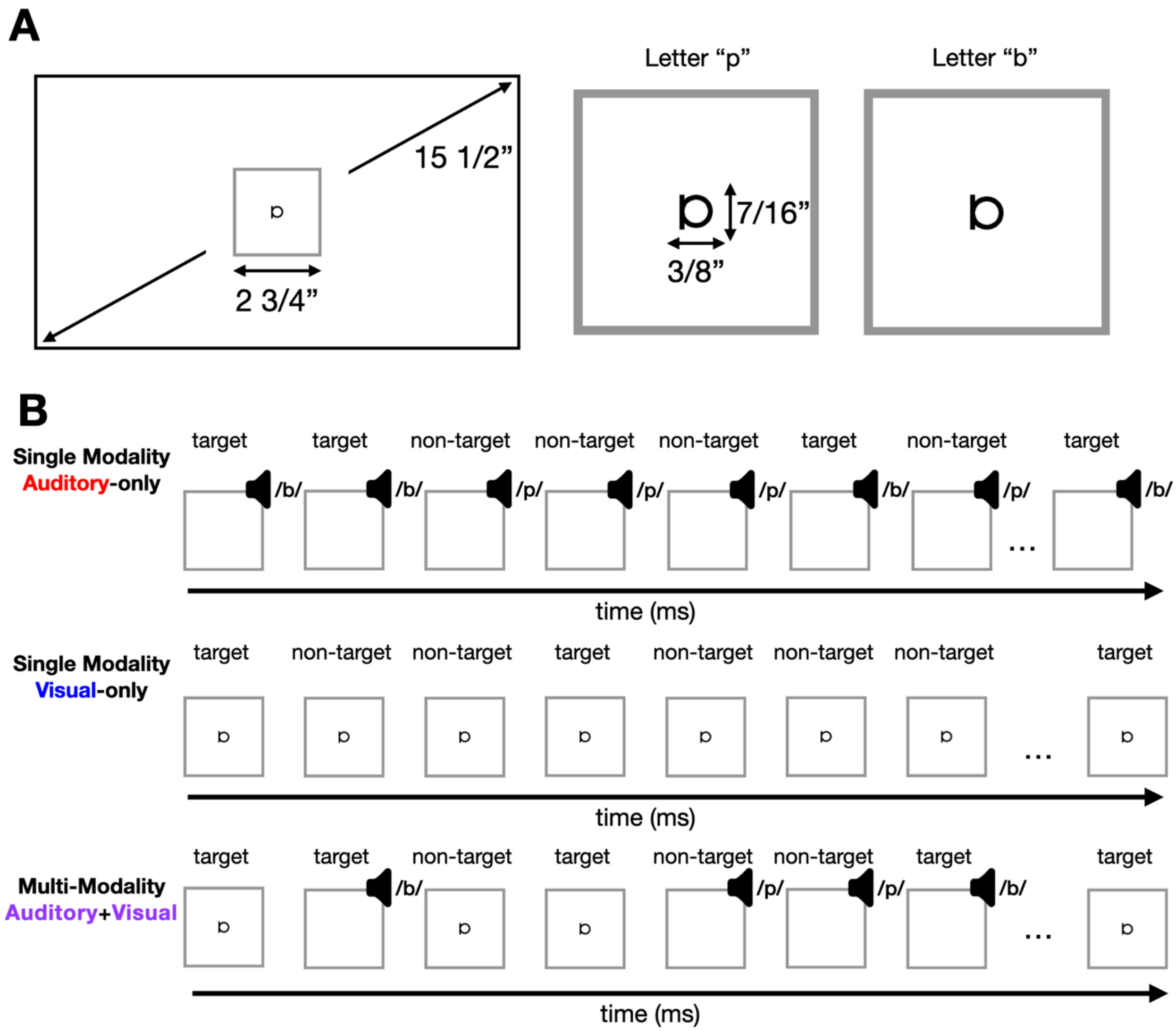

Figure 1. Experimental Set-up

(A) Example display featuring the visual stimulus “p” with the dimensions measured using a 15.6” monitor and the visual stimuli letters “p” and “b” with an ascender/descender length of 5 pixels. (B) Task schematic of the integrated visual and auditory continuous performance task (IVA-CPT) for each condition where the target/critical signal is “b” for the visual modality and /b/ for the auditory modality. The stimuli were presented in random order every 2000ms with a stimulus duration of 167ms for visual and 500ms for auditory.

Results

Questionnaires.

Nine of the 18 participants reported having some musical experience with a mean expertise rating of 2.5 (*SD* = 0.93) on a four-point scale with 1 indicating “novice” level and a 4 indicating “expert” level. This resulted in approximately half the participants in the Auditory-only and Multimodal Auditory+Visual condition having some musical experience and controlled for any bias—bias in discerning non-target and target auditory stimuli—during the auditory trials. Caffeine was used prior to the start of the experiment in 80% of the sessions. Participants reported getting an average of 6.62 hours of sleep (*SD* = 1.33 hours) the night before each experimental session. Participants' reported mood was an average of 5.32 (*SD* = 0.99) on a scale from 1 indicating fatigued to 7 as energized. The sensation questionnaire, used in part to determine if any participants needed to be removed for safety, revealed that all participants reported no adverse reaction to the tDCS, with a reported average sensation of 1.41 (*SD* = 1.11) on a 1-10 point scale, where 1 corresponds to no sensation. The NASA-TLX data on self-reported workload is shown below in **Table 1**.

Table 1. NASA TLX Analysis Summaries

	df	F	p-value
Condition (Auditory-only, Visual-only, Multimodal)	2, 14.39	0.24	.79
Stimulation (anodal, sham)	1, 13.75	2.06	.17
Condition×Stimulation	2, 13.73	0.17	.85

Study sample characteristics are reported in **Table 2**. Age, sex, and music experience did not differ significantly between the vigilance tasks (age: ($F(2,15) = 0.70$, $p = .52$, $\eta_p^2 = 0.09$; sex: $\chi(2) = 1.50$, $p = .47$; music: $\chi(2) = 3.15$, $p = .21$).

Table 2. Demographics by Task Condition

Task Condition	Sample size (n)	# with musical experience (n)	Female n (%)	Age mean (SD)
Auditory-only	6	3	3 (50%)	26.00 (6.10)
Visual-only	6	2	2 (33%)	31.50 (9.92)
Multimodal	6	4	1 (17%)	30.17 (8.82)
All	18	9	6 (33%)	29.22 (8.27)

Specificity (hits).

Analysis results are summarized in **Table 3**. For the modality of audition, condition (Auditory-only, Multimodal) did significantly interact with stimulation type (anodal, sham). Mean specificity values by condition and stimulation type are shown in **Figure 2**. Post-hoc pairwise comparisons for condition found that specificity decreased under anodal tDCS (mean ± SE; 0.51 ± 0.11 TP/AP) compared to sham tDCS (0.61 ± 0.11 TP/AP) in the Auditory-only condition ($p = .037$). Specificity for auditory performance was not significant in the multimodal condition ($p = .16$), with no differences detected in specificity under anodal tDCS (0.49 ± 0.11 TP/AP) compared with sham tDCS (0.42 ± 0.15 TP/AP). No other main effect or interactions were significant for audition and no significant effects were found for vision.

Sensitivity (correct rejections).

During anodal stimulation (0.60 ± 0.07) there was a significant decrease in sensitivity relative to sham tDCS (0.69 ± 0.73) within audition (**Figure 2**). The Condition×Stimulation interaction was significant with respect to vision. Post-hoc pairwise comparisons found that within the Visual-only condition there was a decrease in sensitivity ($p = .005$) during anodal tDCS (0.83 ± 0.06 TN/AN) relative to sham (0.91 ± 0.06). However, the sensitivity for visual stimuli in the Multimodal Auditory+Visual condition was not significantly different (p = .59) during anodal tDCS (0.85 ± 0.06 TN/AN) in comparison to the sham tDCS (0.83 ± 0.06 TN/AN). Other main effects and interactions did not reach statistical significance (**Table 3**).

Reaction time.

Within audition there was a significant Condition×Stimulation interaction (**Table 3, Figure 2**). The random and fixed effects from Session and Block were small based on an examination of the coefficients (approximately zero), so Session and Block were removed from the model. With the more parsimonious model (Condition: $F(1,10.06) = 0.001$, $p = .97$, $\eta_p^2 < 0.01$; Stimulation: $F(1,125.03) = 0.08$, $p = .77$, $\eta_p^2 < 0.01$; Condition×Stimulation: $F(1,125.03) = 5.80$, $p = .018$, $\eta_p^2 = 0.04$) post-hoc pairwise comparisons found that performance in the Auditory-only condition was significantly improved under anodal stimulation, (p = .048), with a decrease in reaction time during anodal stimulation (352 ± 81.9 ms) compared with sham tDCS (422 ± 81.9 ms). The Multi-Modal Auditory+Vision condition did not reach significance (p = .16), finding no discernable difference in performance for the auditory stimulus under anodal tDCS (410 ± 81.9 ms) compared to sham tDCS (355 ± 83.3 ms). Within the vision, there was a significant main effect of stimulation type, where anodal tDCS (497.55 ± 21.12 ms) resulted in faster reaction times relative to sham tDCS (524.83 ± 21.44 ms). No other significant main effects or interactions were detected.

Subjective report (NASA-TLX).

Analyses were conducted on average cumulative NASA-TLX ratings. **Table 1** shows the results of the linear mixed model analyses carried out to assess the effects of condition (Auditory-only, Visual-only, Multimodal Auditory+Visual), tDCS stimulation (anodal, sham), and their interaction on participant perceived workload. Conditions did not differ detectably in workload ratings (Auditory-only: 8.50 ± 0.99 score; Visual-only: 9.34 ± 0.99 score; Multimodal: 9.34 ± 1.01 score). Moreover, Stimulation Type was not statistically significant (anodal: 9.46 ± 0.63 score; sham: 8.66 ± 0.65 score).

Table 3. Linear Mixed Model Summaries

	Audition performance				Vision performance			
	df	F	p	η_p^2	df	F	p	η_p^2
Specificity (hits)								
Block (I-VI)	5, 103.08	0.35	.88	0.02	5, 102.87	1.57	.18	0.07†
Condition (single, multimodal)	1, 10.03	0.44	.44	0.04	1, 9.94	1.48	.25	0.13†
Stimulation (anodal, sham)	1, 45.44	0.07	.79	<0.01	1, 98.84	0.24	.63	<0.01
Block×Condition	5, 103.08	0.32	.90	0.02	5, 102.87	0.44	.82	0.02
Block×Stimulation	5, 103.08	0.84	.53	0.04	5, 102.87	0.31	.90	0.01
Condition×Stimulation	1, 104.61	8.15	**.005***	0.07†	1, 98.84	3.6	.06	0.04
Block×Condition×Stimulation	5, 103.08	0.25	.94	0.01	5, 102.87	1.15	.34	0.05
Sensitivity (correct rejections)								
Block (I-VI)	5, 103.06	0.46	.80	0.02	5, 103.13	1.42	.22	0.06†
Condition (single, multimodal)	1, 10.05	0.38	.55	0.04	1, 10.11	0.22	.65	0.02
Stimulation (anodal, sham)	1, 53.66	12.09	**.001***	0.18†	1, 104.63	1.98	.16	0.02
Block×Condition	5, 103.06	0.06	1.00	<0.01	5, 103.13	0.61	.70	0.03

Block×Stimulation	5, 103.06	0.8	.56	0.04	5, 103.13	0.19	1.00	<0.01
Condition×Stimulation	1, 104.53	1.46	.23	0.01	1, 104.63	5.17	**.03***	0.05
Block×Condition×Stimulation	5, 103.06	0.46	.81	0.02	5, 103.13	0.67	.65	0.03
Reaction time								
Block (I-VI)	5, 100.09	0.42	.84	0.02	5, 104.16	0.57	.72	0.03
Condition (single, multimodal)	1, 10.05	0.01	.93	<0.01	1, 10.15	<0.001	.99	<0.01
Stimulation (anodal, sham)	1, 101.01	0.71	.40	<0.01	1, 105.62	4.42	**.04***	0.04
Block×Condition	5, 100.09	0.4	.85	0.02	5, 104.16	0.22	.95	0.01
Block×Stimulation	5, 100.09	0.68	.64	0.05	5, 104.16	0.82	.54	0.04
Condition×Stimulation	1, 101.01	4.67	**.03***	0.05	1, 105.62	1.68	.20	0.02
Block×Condition×Stimulation	5, 100.09	0.38	.86	<0.01	5, 104.16	0.54	.74	0.03

Significant correlations (p<.05) are indicated in bold with an asterisk (*), medium (η_p^2=0.06) or larger effect sizes are denoted with a cross (†)

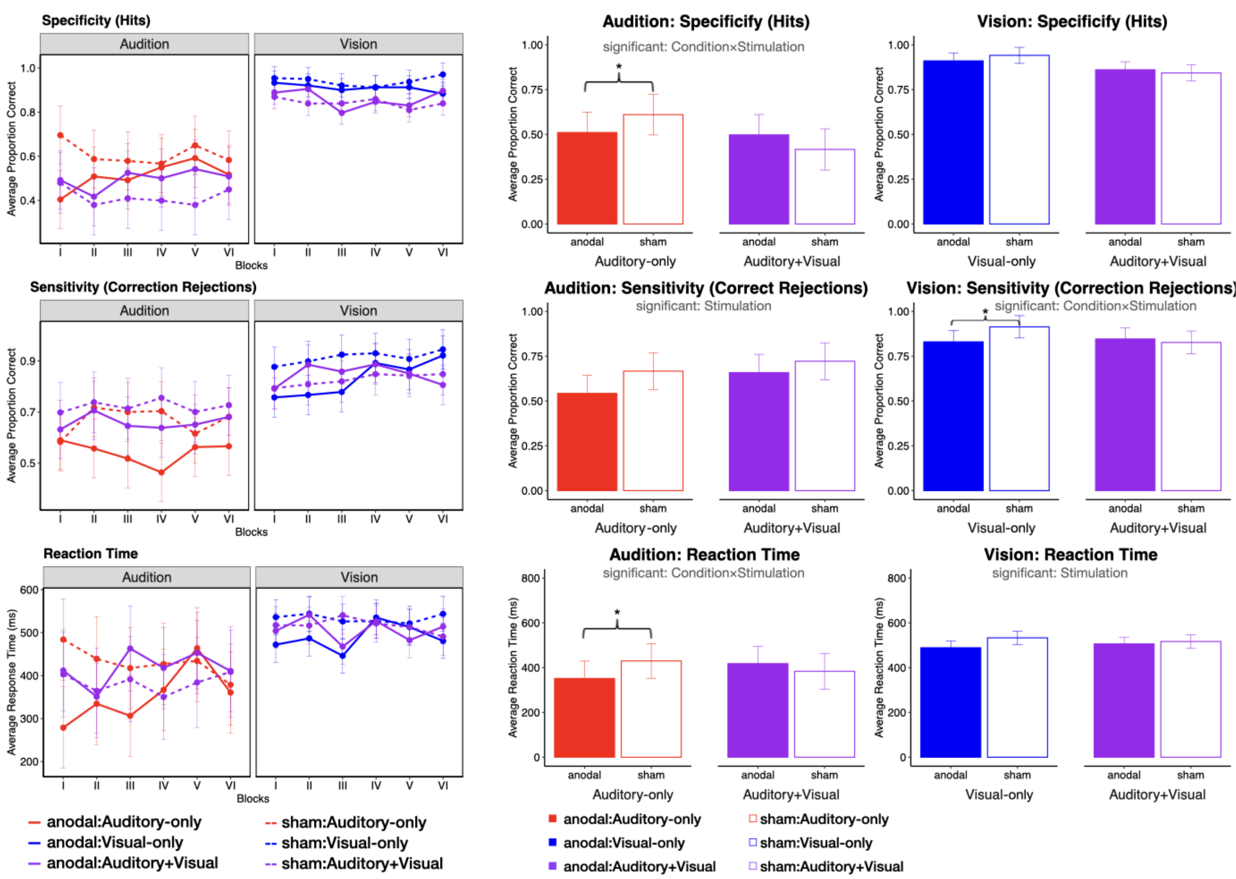

Figure 2. Results

(Top row) Specificity (target hits), (Middle row) Sensitivity, and (Bottom row) Average Reaction Time for the Auditory-only (red), Visual-only (blue) and Auditory+Visual (purple) by modality (audition and vision).

Discussion

The DLPFC is a key region that is part of the central executive network supporting higher order cognitive processes. Neuroimaging and lesion studies suggest that some of the prominent functions of the DLPFC include attention, memory, planning, and updating.[50-52] The current study evaluated whether anodal tDCS stimulation to the right DLPFC affects performance outcomes on a sustained attention task differentially depending on the time on task, the task modality (audition, vision), or the number of modalities that needed to be monitored (single, multimodal). The study found no differences in performance with time on task between tDCS stimulation conditions, indicating a lack of vigilance decrement within the overall vigilance tasks. However, in addition to providing further evidence of improved performance with faster reaction times during anodal tDCS within the visual modality,[8,14,15] results show performance enhancements within the auditory modality. Specifically, in the single auditory condition, reaction times were faster when participants received anodal tDCS relative to sham tDCS. Notable results were also associated with anodal tDCS stimulation and the interaction with the number of modalities monitored. However, along with this positive effect of anodal stimulation, we also found conditions where anodal stimulation resulted in no benefit (no discernable changes in specificity for the auditory stimuli in the multimodal condition or for all visual stimuli, no change in sensitivity for the visual stimuli in the multimodal condition, no significant changes in perceived workload as measured by the NASA-TLX), or even worsened performance relative to sham stimulation (decreased sensitivity in the single auditory conditions, decreased sensitivity for the single visual condition).The mixed set of significant and null outcomes highlight the complexity of tDCSs' modulatory role of the DLPFC during an attentionally-demanding task.

A primary goal of the current study was to investigate the effects of anodal tDCS on the modulation of performance over time, and evaluate its potential as a countermeasure against the vigilance decrement. The maintenance of vigilance[5,6] requires a sufficient amount of cognitive resources to perform an often monotonous task. Maintaining vigilance depletes cognitive resources, as reflected by decreased blood flow and oxygenation in the DLPFC, as measured by positron emission tomography and functional near-infrared spectroscopy.[17,53] While enhancements to vigilance-based performance have been reported,[8,14,17] not all studies have found positive improvements with tDCS. Research using the go/no-go response paradigm often employed in sustained attention studies[54] reported no significant performance differences between anodal and sham stimulation.[55,56] The researchers in the study hypothesized that the task's inhibitory control demands were low, and that participants were already performing at ceiling to benefit from stimulation. The current study did not find significant evidence that the IVA-CPT task produced a vigilance decrement during sham tDCS. It was, therefore, unsurprising that enhancements with anodal tDCS did not differ from sham tDCS over time. It is possible that the IVA-CPT and the testing environment demanded higher levels of engagement than traditional vigilance tasks such as the Mackworth Clock Test[57] or the Psychomotor Vigilance Task.[15] However, prior research using the IVA-CPT did show an auditory vigilance decrement.[35] Moreover, the IVA-CPT task was consistent with the first criterion for a vigilance decrement to occur according to resource theory, namely that the task was resource-demanding. The vigilance tasks had an event rate of 30 per minute, which was within enough range of other vigilance tasks[58] to qualify as resource-demanding and sufficient for a vigilance decrement. However, it may have been the case that maintaining a relatively steady level of arousal throughout the task was beneficial for vigilance-based performance. For example, learning effects may have contributed to the increased engagement with the task. Studies have suggested that self-report on levels of arousal may serve as a measure of available attentional resources.[59,60] While the current study did collect self-ratings of mood and fatigue at the start of the session this was not re-assessed at the end of the session. To tease apart the interaction between task engagement and the depletion of cognitive resources, future studies should collect the participants' subjective reports of engagement during the task to measure levels of tiredness, fatigue, apathy, and distractibility.

Subjective reports of workload found no differences between stimulation or vigilance condition. All three vigilance tasks scored at the scale's midpoint, on average, indicating that all of the task conditions were perceived as moderately cognitively demanding,[6] and evidence of the second requirement needed for the vigilance decrement. In addition, while participants were blind to the stimulation type received at each session, they did not indicate any differences in workload between the two sessions (note: participants were not asked to guess which sessions were the real/sham sessions, so it is possible that they discerned which session was which). If the stimulation were increasing available cognitive resources, it would be expected that task demands would be lower in the anodal tDCS session. Given that behavioral performance was mixed, the NASA-TLX may not have been a sensitive enough workload measure to detect any improvements in workload and performance. It may also be possible that a participant's subjective report is separable from the objective measures.

A second aim of the current study was to contribute to the sparse literature investigating the effects of anodal tDCS over the DLPFC during an auditory sustained attention task. Among other roles in auditory processing, the DLPFC is associated with auditory attention.[61,62] The facilitatory effects of anodal tDCS manifested as faster reaction times in both the visual and single auditory modalities. However, these faster reaction times may have been due to a speed accuracy tradeoff because while reaction times improved, sensitivity and specificity decreased in some cases. Dedoncker and colleagues[63] reported that healthy participants were found to be responding significantly faster following anodal tDCS compared to sham stimulation in a meta-analysis. Further research is needed to probe these effects that may be indicative of hyperactivity and impulsivity. Indeed, research has found cathodal tDCS increased false alarm errors[64,65] and anodal stimulation of the inferior frontal gyrus decreased impulsivity.[66] Future studies may want to require participants to practice to minimize any speed-accuracy tradeoffs that may be occurring.

Decreases in sensitivity were also observed in the single visual modality condition with anodal tDCS, compared to sham. This decrease in sensitivity suggests that participants were more likely to falsely identify non-targets as targets with the application of anodal tDCS. These results are consistent with some reports of increased false memory/recognition rates.[67] The current study by design increased the difficulty of discrimination[35] between the two stimuli, target and non-target, creating favorable conditions for increased false alarm rates. These results demonstrate a pattern similar what anodal tDCS has on performance in single modality auditory and visual tasks.

When increasing the number of modalities that were monitored during task performance from one to two, it was posited that the addition of another modality would expend resources more rapidly than a single modality. However, performance on the multimodality task showed trends in auditory sensitivity and visual reaction times similar to the single modality counterparts. Based on the objective performance data, it appears that there was no difference in task difficulty or resource demands between the multimodal and unisensory conditions. In addition, there were no significant main effects of task condition (single versus multimodal) on any of the dependent measures, but there were several task conditions by stimulation interactions. Although interpreting null results should be approached with caution, the results revealed that for vision, contrary to the single modality visual task, anodal tDCS showed no discernable changes in sensitivity to the visual stimulus during the multimodal modality task compared to sham. Within audition, there were no significant changes in specificity or reaction times with anodal tDCS during the multimodality vigilance task to the auditory stimuli. Taken together, these cross-modal comparisons indicate that effects of anodal tDCS do not strictly improve performance but may have differential effects depending on modality, number of modalities, and the performance outcome measure.

The multimodality condition in the current study presented either the visual or auditory signal in a random serial pattern, requiring the subject to switch their attention between the auditory and visual stimuli. A future study may want to extend the use of tDCS by testing a true dual task that requires attention to both auditory and visual stimulus at the same time by presenting the stimuli visually and audibly together. Here, some trials would present the same letter with both stimuli and other trials would present conflicting stimuli to further understand how tDCS may modulate performance on dual visual/auditory tasks. Research indicates that when visual and auditory stimuli are presented simultaneously, some performance effects with tDCS impact stimuli integration.[68] The postulated effects of tDCS for conflicting auditory/visual information may result in improved performance.

Prior research using anodal tDCS also found different effects on specificity and sensitivity measures.[23] Karthikeyan, Smoot, and Mehta (2021) noted that the differences in the effects of anodal tDCS on specificity and sensitivity performance outcome measures may be related to the different brain regions involved during processes of response selection for targets and response inhibition for non-targets.[69] These cortical structures may have also been influenced by the tDCS current (density and intensity), resulting in these distinct effects. Furthermore, the differences found based on the number of modalities monitored may also be related to different networks that were impacted by stimulations. The multimodal condition, Visual+Auditory, may be relying on brain networks supporting both modality-specific and non-specific processes. Brain areas that have been implicated in both auditory and visual vigilance include the prefrontal cortex, anterior insula, and subcortical areas, such as the thalamus.[70] Modality-specific effects have found Broca's region and the parietal cortex involved during auditory vigilance and the occipital cortex during visual vigilance.[70] While the DLPFC served as the targeted area, models of current density suggest the electrical current is diffused beyond the stimulation sites and downstream effects are not limited to the specific stimulated site.[71] Future research should continue to investigate these modality-specific effects and the underlying brain regions supporting auditory, visual, and multimodal vigilance processes.

Though this study features a number of notable strengths, such as the calibration of the stimuli to create equally discriminable stimuli across modalities, there are some limitations that can be improved upon in future work. To increase the ecological validity of the vigilance task, the length of the sustained attention task should be increased and military-relevant stimuli (e.g., sonar monitoring, which has visual and auditory signals) should be used to better represent the challenges of a real-world, multisensory tasks like military watchstanding, in which task duration can extend beyond eight hours. Assessing performance in extended durations may also overcome potential learning effects and thus expose performance decrements. An additional limitation is that the modest sample size did not permit an analysis of individual differences, which could potentially be an important factor to investigate as the vigilance decrement shows individual variation.[72] Some individuals experience performance decrements in as little as ten minutes whereas others are resistant to performance declines following 30-minutes of task. There are also variations within a single individual, where a person may not exhibit a decrement that was measurable the previous day.[73] Additional studies are needed to replicate and expand on the results of this current study. While the current study controlled for the time-of-day testing within participants, the between participants testing times varied producing possible performance difference from internal circadian timing, however the self-reported average mood of participants in the current study was near energized.

The current study showed inconsistent effects of tDCS in tasks that required monitoring auditory stimuli, visual stimuli, or auditory and visual stimuli simultaneously. Because the task did not induce a vigilance decrement in any of the three conditions, the potentially differential effects of tDCS on the different forms of stimuli could not be evaluated. More research using a task that successfully induces a vigilance decrement is needed to understand the potential interaction between anodal stimulation and multimodality performance before tDCS can be used to augment performance of healthy individuals.

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Appendix

TDCS Sensation Questionnaire

SQ

This section is to be filled out by Research Associate only

Subject ID #: ______ *

Date: ______

Session: Select... *

Time TDCS Started: ______ * *Time TDCS Finished:* ______ *

RA: Select... *

Participant: Please fill out each of the following sections when instructed by Research Associate.

Measure 1: Baseline

Time: ______ *

To what degree are you experiencing the following sensations at the electrode site(s)?

	None	Mild			Moderate			Severe		Unbearable	
	0	1	2	3	4	5	6	7	8	9	10
Itching	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Pain	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Heat	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Discomfort	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

For Participant:
Please answer the following questions honestly and to the best of your ability.
All questions apply to your **current** mood.

fatigued *tired; overcome with physical or mental esertion*	☐	☐	☐	☐	☐	☐	☐	**energized** *invigorated; prepared for activity*

Please explain.

Additional Comments

Measure 2: 4 minutes after start s after start

Time: ______ *

To what degree are you experiencing the following sensations at the electrode site(s)?

	None	Mild			Moderate			Severe		Unbearable	
	0	1	2	3	4	5	6	7	8	9	10
Itching	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Pain	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Heat	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Discomfort	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

For Participant:
Please answer the following questions honestly and to the best of your ability.
All questions apply to your **current** mood.

fatigued *tired; overcome with physical or mental esertion*	☐	☐	☐	☐	☐	☐	☐	**energized** *invigorated; prepared for activity*

Please explain.

Additional Comments

Supplemental Figure 1.
Sensation Questionnaire.