USAARL-JAOA-PV--2026-13

UNITED STATES ARMY AEROMEDICAL RESEARCH LABORATORY

Transcranial Direct Current Stimulation and Aviator Performance During Simulated Flight (Reprint)

Kathryn A. Feltman & Amanda M. Kelley

Notice

Qualified Requesters

Qualified requesters may obtain copies from the Defense Technical Information Center (DTIC), Fort Belvoir, Virginia 22060. Orders will be expedited if placed through the librarian or other person designated to request documents from DTIC.

Change of Address

Organizations receiving reports from the U.S. Army Aeromedical Research Laboratory on automatic mailing lists should confirm correct address when corresponding about laboratory reports.

Disposition

Destroy this document when it is no longer needed. Do not return it to the originator.

Disclaimer

The views, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other official documentation. Citation of trade names in this report does not constitute an official Department of the Army endorsement or approval of the use of such commercial items.

Human Subject Use

In the conduct of research involving human subjects, the investigator(s) adhered to the policies regarding the protection of human subjects as prescribed by Department of Defense Instruction 3216.02 (Protection of Human Subjects and Adherence to Ethical Standards in DoD-Supported Research) dated 8 November 2011.

IRB Determination and Number

This study, USAARL 2019-14, was approved by the Medical Research and Development Command Institutional Review Board on 2 March 2020.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
18-03-2026	Publisher's Version	2024

4. TITLE AND SUBTITLE

Transcranial Direct Current Stimulation and Aviator Performance During Simulated Flight (Reprint)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Feltman, K. A.[1], & Kelley, A. M.[1]

5d. PROJECT NUMBER

MO210121

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Aeromedical Research Laboratory
P.O. Box 620577
Fort Rucker, AL 36362

8. PERFORMING ORGANIZATION REPORT NUMBER

USAARL-JAOA-PV--2026-13

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Medical Research and Development Command Military
Operational Medicine Research Program
504 Scott Street
Fort Detrick, MD 21702-5012

10. SPONSOR/MONITOR'S ACRONYM(S)

MRDC MOMRP

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A. Approved for Public Release: distribution is unlimited.

13. SUPPLEMENTARY NOTES

[1]U.S. Army Aeromedical Research Laboratory

14. ABSTRACT

Transcranial direct current stimulation (tDCS) is a promising method for maintaining cognitive performance. Anticipated changes in rotary-wing aircraft are expected to alter aviator performance. A single-blind, randomized, sham-controlled study evaluated effects of 2-mA anodal tDCS to the right posterior parietal cortex on aviator performance within a Black Hawk simulator. A mixed design with one between-subjects factor was assessed: stimulation prior to flight (20 constant min) and during flight (two timepoints for 10 min each). The within-subjects factor included active vs. sham stimulation. Randomly assigned to each stimulation group were 22 aviators. Aircraft state metrics derived from the simulator were used to evaluate performance. Subjects completed two flights (active stimulation and sham stimulation) with an in-flight emergency introduced at the end to assess whether the timing of tDCS application (prior to or during flight) affected the ability to maintain attention and respond to an unexpected event. Results found active stimulation during flight produced statistically significant improvements in performance during the approach following the in-flight emergency. Subjects in the during flight group maintained a more precise approach path with glideslope values closer to zero ($M = 0.05$) compared to the prior-to-flight group ($M = 0.15$). The same was found for localizer values (during flight, $M = 0.07$; prior-to-flight, $M = 0.17$).

15. SUBJECT TERMS

transcranial direct current stimulation, performance enhancement, aviation, sustained attention

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UNCLAS	UNCLAS	UNCLAS	SAR	10	Amanda Hayes, MS
					19b. TELEPHONE NUMBER *(Include area code)* 334-255-6067

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

14. Abstract (continued)

There were no statistically significant differences between groups on secondary outcome measures. These findings suggest stimulation during flight may assist in maintaining cognitive resources necessary to respond to an unexpected in-flight emergency. Moreover, blinding efficacy was supported with 32% of subjects correctly guessing when active stimulation was being delivered (52% correctly guessed the sham condition).

Transcranial Direct Current Stimulation and Aviator Performance During Simulated Flight

Kathryn A. Feltman; Amanda M. Kelley

INTRODUCTION: Transcranial direct current stimulation (tDCS) is a promising method for maintaining cognitive performance. Anticipated changes in rotary-wing aircraft are expected to alter aviator performance.

METHODS: A single-blind, randomized, sham-controlled study evaluated effects of 2-mA anodal tDCS to the right posterior parietal cortex on aviator performance within a Black Hawk simulator. A mixed design with one between-subjects factor was assessed: stimulation prior to flight (20 constant min) and during flight (two timepoints for 10 min each). The within-subjects factor included active vs. sham stimulation. Randomly assigned to each stimulation group were 22 aviators. Aircraft state metrics derived from the simulator were used to evaluate performance. Subjects completed two flights (active stimulation and sham stimulation) with an in-flight emergency introduced at the end to assess whether the timing of tDCS application (prior or during flight) affected the ability to maintain attention and respond to an unexpected event.

RESULTS: Results found active stimulation during flight produced statistically significant improvements in performance during the approach following the in-flight emergency. Subjects maintained a more precise approach path with glideslope values closer to zero (M = 0.05) compared to the prior-to-flight group (M = 0.15). The same was found for localizer values (during flight, M = 0.07; prior to flight, M = 0.17). There were no statistically significant differences between groups on secondary outcome measures.

DISCUSSION: These findings suggest stimulation during flight may assist in maintaining cognitive resources necessary to respond to an unexpected in-flight emergency. Moreover, blinding efficacy was supported with 32% of subjects correctly guessing when active stimulation was being delivered (52% correctly guessed the sham condition).

KEYWORDS: transcranial direct current stimulation, performance enhancement, aviation, sustained attention.

Feltman KA, Kelley AM. ***Transcranial direct current stimulation and aviator performance during simulated flight*****. Aerosp Med Hum Perform. 2024; 95(1):5–15.**

Changes to technology in current and future Army rotary-wing aircraft pose threats to the effectiveness of the human operators who work within those systems. Technological changes include automating tasks previously performed by the human operator. For example, the Altitude Hold and Hover Stabilization system is a new rotary-wing technology used to automate aviator tasks. Although this system is currently only in a few airframes within the U.S. Air Force, technology similar to this will eventually be in all U.S. military rotary-wing airframes. Typically, the intent of flight automation is to reduce aviator cognitive workload by offloading certain tasks to a computer; however, in doing so, it does not fully remove the task from the aviator's awareness. Rather, automating critical tasks shifts the role of the aviator from direct control of the aircraft to that of a supervisor of the system.[32] In these cases, the aviator becomes responsible for monitoring the computer system that is now in control of the aircraft. This is done by providing system inputs, such as desired altitude, and ensuring that the system is performing as expected. Such scenarios

---

From the U.S. Army Aeromedical Research Laboratory, Fort Novosel, AL, United States.

This manuscript was received for review in February 2023. It was accepted for publication in October 2023.

Address correspondence to: Katie Feltman, Ph.D., Research Psychologist, U.S. Army Aeromedical Research Laboratory, 8121 Kidd St., Alexandria, VA 22309, United States; feltmank@gmail.com.

DOI: https://doi.org/10.3357/AMHP.6243.2024

do not fully reduce the aviator's experience of workload, but can alter it, shifting workload around the flight in a manner that can precipitate disengagement, complacency, and deterioration of situation awareness.

The shift in workload that results from increased automation can lead to performance decrements if the aviator begins to experience monotony, loss of vigilance, task disengagement, and/or boredom. Indeed, previous studies have shown that automation can lead to several negative consequences, such as overreliance, complacency, and loss of task engagement,[20] which in turn can negatively affect overall performance. In the case of the Army aviator (present and future), maintaining vigilance is necessary to monitor any system inaccuracies. Additionally, aviators need to maintain spare cognitive capacity for processing and responding to changes in mission requirements. For example, an aircraft malfunction or an abrupt change in mission parameters would require aviators to have adequate cognitive capacity to properly respond. While system design would be the optimal method for aiding aviators in attention maintenance, this has often failed and other means, such as caffeine and pharmaceuticals, have been explored and used (e.g., Kelley et al.[13]). An alternative to these interventions is the use of transcranial electrical stimulation (tES). tES tends to have fewer undesirable side effects in comparison to caffeine and pharmaceuticals. It is also a portable, compact, and inexpensive technique, making it a candidate for operational use. One promising type of tES is transcranial direct current stimulation (tDCS).

tDCS uses a weak electrical current to modulate neuronal activation thresholds and induce transient long-term potentiation and depression effects. These effects then produce shifts in cortical excitability, resulting in changes to neuronal firing rates and timing of firing. For a full overview of the suspected mechanisms of action, the reader is referred to Sudbrack-Oliveira et al.[28] Importantly, tDCS has a well-established safety profile and has been associated with minimal side effects. Recent reviews of the safety and tolerability of tDCS for psychiatric treatment in children and adolescents have found no concerns for its safety and tolerability in sessions ranging from 1 to 20 min, with tDCS applied at 2 mA for up to 20 min.[4] More recently, tolerability was evaluated in 308 subjects (all diagnosed with some sort of medical condition) who used tDCS across multiple sessions.[22] Again, no adverse events were noted. To the best of the authors' knowledge, the effects of repeated sessions have not yet been examined in nonclinical populations. Compared to current methods of sustaining attention in aviators, such as modafinil and caffeine, tDCS may be a better candidate. For example, caffeine consumption is known to delay sleep onset (see Clark and Landolt[6] for a review). Caffeine consumed as long ago as 6 h prior to going to bed can significantly reduce total sleep time.[7] This side effect makes it a less ideal candidate for maintaining or enhancing performance in operational settings. Modafinil, alternatively, has documented side effects that include, but are not limited to, nausea, headache, and diarrhea,[11] as well as very rare but potentially fatal reactions to the medication. Additionally, individuals may build a tolerance to modafinil, requiring increased dosages to receive the same benefits. tDCS, while also prone to some undesirable side effects such as burning sensations, skin irritation, and headaches, has no documented negative effects on sleep, nor likelihood of building a tolerance (however, these topics require further research). Thus, tDCS may be a feasible alternative for combating deficits in vigilance within operational aviation conditions involving the use of automated systems.

The efficacy of tDCS depends on a number of factors. These factors include, but are not limited to, the target brain region, the timing of stimulation delivery (e.g., during a task, prior to a task), and individual differences in susceptibility to the effects of stimulation.[31] Identifying the correct region of the brain to target with stimulation is critical in increasing the likelihood of effective behavioral outcomes. Typically, researchers aim to stimulate the region of the brain responsible for the task under study.[3] When to deliver the stimulation is also a critical component, given that the duration of effects do not appear to go beyond 1 h. Moreover, much of the literature to date suggests tDCS is most effective when the person is already actively engaging the targeted brain region.[33] Recently, it has been demonstrated that tDCS specifically alters behavioral performance as a result of engaging the task-related functional networks while tDCS is being delivered.[23]

The posterior parietal cortex (PPC) is well-established as playing a significant role in directing and maintaining attention in humans.[27,30] Moreover, there is evidence to suggest that right-lateralized brain networks play a pivotal role in vigilance. A review by Langner and Eickhoff[15] suggested that right-lateralized regions, including the dorsomedial, mid- and ventrolateral prefrontal cortex, anterior insula, parietal cortex, and several subcortical areas, mediate vigilance. An additional review of studies using transcranial Doppler sonography during vigilance tasks confirmed that decreases in right-hemisphere blood flow velocity over time occurred that corresponded with behavioral responses consistent with the vigilance decrement.[32] Thus, this evidence further supports the right lateralization of vigilance.

To date, several studies have examined the use of tDCS in mitigating vigilance decrement. Reteig et al.[24] reviewed nine studies that applied tDCS in a variety of sustained attention paradigms. Of the nine studies, only one[17] targeted the parietal cortex while the remaining eight targeted the frontal cortex. Li et al.[17] found increased reaction times with the application of tDCS, suggesting worsened performance. The remaining studies that targeted the frontal cortex found mixed results. Moreover, of the nine studies, only one used an applied task.[19] In their study, the researchers applied each active anodal and active cathodal tDCS to the frontal cortex (F3, F4) during an air traffic control simulation. They found that both active anodal and active cathodal tDCS prevented performance decline compared to sham stimulation. Furthermore, the researchers also manipulated when the stimulation was delivered, and found that those who received stimulation early in the task benefited more than those who received it later in the task.

More recently, Lo et al.[18] evaluated the effects of tDCS applied to the right PPC on three aspects of attention: orienting, alerting, and executive control. They found that, compared to sham tDCS, active anodal tDCS to the right PPC improved performance on orienting attention. Although the authors did not examine vigilant attention per se, this finding suggests tDCS over the right PPC can modulate attentional processes. Given the established role of the PPC in maintaining attention,[27,30] it is reasonable to postulate targeting this region of the brain via tDCS may also aid in the maintenance of attention during a sustained attention task. Although worsened performance was demonstrated with tDCS applied to the parietal cortex, their findings may have been due to the montage applied.[17] Specifically, in the condition where performance was impeded, the anodal electrode was applied to the right parietal cortex and the cathode applied to the left; the authors hypothesized that the cause of the decrement was due to the left parietal cortex being inhibited by the stimulation. Alternatively, Lo et al.[18] placed the anodal electrode over the right parietal cortex and the cathodal electrode over the left supraorbital region. This difference in placements may have contributed to the differences in behavioral results.

Much of the literature suggests tDCS is most effective when applied while a person is actively engaged in the task of interest.[23] In addition, when involved in a task that requires sustained attention over an extended period of time, performance tends to wane around 30 min into the task.[21] Therefore, applying stimulation during a task where sustained attention is required may result in performance maintenance compared to applying it prior to the task. Recently, it has been demonstrated that tDCS applied during a 1-h long, demanding working memory task resulted in preserved performance as compared to the sham condition.[12] However, some studies have found support for the application of offline tDCS for maintaining or improving performance.[18] Applying tDCS prior to the task has more feasibility for applied settings such as aviation where it may not be safe to apply tDCS during flight. For tDCS to be applied during flight, a system would need to be compatible with the aviator's helmet. This is something, however, that may be possible in the near future, given the current efforts underway for developing methods for operator state monitoring.[8]

The primary aim of the current study was to evaluate whether 2 mA, applied for 20 min total, anodal tDCS to the right PPC can maintain or improve aviator performance during simulated flight requiring vigilance. A secondary aim of the study was to evaluate the effects of the timing of stimulation delivery. Specifically, we were interested in whether stimulation delivered prior to flight would be as effective as stimulation delivered during flight. This would inform the utility of tDCS for operational flight. The following hypotheses were tested in support of these aims:

1. Hypothesis 1: Active stimulation compared to sham stimulation will improve aviator performance.
2. Hypothesis 2: Application of tDCS during flight will result in greater performance improvements compared to tDCS prior to flight.

Finally, we also sought to evaluate perceptions of tDCS. For this aspect of the study, we evaluated both the blinding efficacy of the study and perceptions regarding its use in military applications. No formal hypotheses were tied to this aspect of the study; rather, this was collected as exploratory information.

METHODS

This study employed a single-blind, randomized, sham-controlled, mixed design to evaluate the main effects of stimulation and timing of delivery on flight performance. There was one within-subjects factor, stimulation mode, with two levels: active stimulation and sham stimulation. There was one between-subjects factor, timing of stimulation delivery, with two levels: prior to the flight (prior-to-flight) and during the flight (during-flight). This study's design, hypotheses, and analyses were preregistered at ClinicalTrials.gov.

Single-blinding was used in this study due to safety concerns. Although tDCS has been demonstrated as safe to use, no literature exists to date (to the authors' knowledge) detailing its use within a motion flight simulator and while wearing communications headsets. Thus, we chose to use a single-blind approach where the subject was blind to the stimulation mode (active or sham) and the research team was able to monitor impedance values and device functionality. To maintain subject blinding, the research team periodically checked device impedances during the sham delivery. The order of stimulation mode (active or sham) was randomized among subjects, such that half received active stimulation first and half received sham stimulation first.

Subjects

The U.S. Army Medical Research and Development Command Office of Research Protections Institutional Review Board reviewed and approved the protocol for this study. Researchers conducted all procedures according to institutional ethical standards. Prior to participation, all subjects provided informed written consent. The data reported here are a subset of data from a larger study.[9] During the consent process, subjects were informed of the nature of the study and the two types of stimulation (active and sham) that would be administered.

There were 26 male Army rotary-wing aviators who participated in the study. They were recruited from the Fort Novosel, AL, area through flyers and word of mouth. Two subjects were withdrawn due to inability to complete both flights and two were excluded due to screening failures. The mean age of the remaining 22 subjects was 36.69 yr (SD = 2.75). Subjects were randomly assigned to one of two groups: 10 subjects in the prior-to-flight stimulation group, and 12 subjects in the during-flight stimulation group. Randomization was done by subject number (odd numbers were assigned to prior-to-flight and even to during-flight). Subjects' flight time within the previous 90 d ranged from 100 to 350 h, with a mean of 214 h (SD = 74.90 h). None of the subjects scored within the clinical range for attention deficit hyperactivity disorder (ADHD) as measured by the Adult ADHD Self-Report Scale (scores ranged 0 to 3, M = 0.68, SD = 1.03; scores of four or higher are highly consistent with ADHD in adults),[1,14] nor for depression using the Beck Depression Inventory [scores ranged from 0 to 4, M = 0.18, SD = 0.85, indicative of minimal depression (0 to 13)].[2] Subjects were compensated monetarily for their time.

All subjects were required to adhere to the following guidelines prior to data collection: a minimum of 6 h of sleep (recorded by actigraphy watch; self-report used for two subjects due to technical failure), refrain from caffeine and medications that cause drowsiness (16 h), nicotine (2 h), and alcohol (24 h) throughout the duration of the study (assessed by self-report). All subjects were screened by the study physician to ensure they had no underlying health concerns that might interfere or cause harm with the application of stimulation (summarized in **Table SI** in **Appendix A**; found online at https://doi.org/10.3357/amhp.6243sd.2024), as well as whether caffeine habits might cause withdrawal symptoms that could impact the study. One subject was disqualified for medical reasons. Additionally, subjects were screened by the study's research pilots (RPs) to ensure their ability to meet performance standards for participation in the study (all screened subjects were able to meet performance standards).

Materials and Equipment

Several questionnaires and survey instruments were used to screen subjects for eligibility, collect demographic information, evaluate blinding efficacy, and evaluate side effects and perceived usability of tDCS. These are summarized below. All in-house developed instruments are provided in the supplemental material (found online at https://doi.org/10.3357/amhp.6243sd.2024).

Medical screening was completed using an in-house developed questionnaire (see **Appendix B**, found online at https://doi.org/10.3357/amhp.6243sd.2024). The questionnaire includes 52 items asking yes/no questions regarding various health concerns (e.g., implanted devices) and current medications and substances (alcohol, caffeine, nicotine) used. Demographic information was collected using an in-house developed questionnaire (see Appendix B, found online at https://doi.org/10.3357/amhp.6243sd.2024). In addition to medical screening, subjects were screened for ADHD symptoms and depressive symptoms. ADHD symptoms were measured using the Adult ADHD Self Report Scale Symptom Checklist.[14] Depressive symptoms were assessed using the Beck Depression Inventory.[2]

Side effects from the application of tDCS were measured using an in-house developed questionnaire (see **Appendix C**, found at https://doi.org/10.3357/amhp.6243sd.2024). This questionnaire is an adaptation of Thair et al.'s[29] side effects questionnaire. Subjects rate the severity of 14 symptoms on a Likert-type scale ranging from 1 (absent) to 10 (severe). There were two additional questionnaires related to the application of the stimulation. One was administered after each stimulation session (post-stimulation questionnaire, **Appendix D**, found at https://doi.org/10.3357/amhp.6243sd.2024) and one that was administered at the completion of the study (poststudy questionnaire, **Appendix E**, found online at https://doi.org/10.3357/amhp.6243sd.2024). The post-stimulation questionnaire was developed in house based on recent research on the efficacy of blinding procedures in studies examining tDCS, while the post-study questionnaire was intended to gauge subjects' comfort with the potential to use tDCS as a cognitive enhancement tool.

Finally, workload was measured using the NASA Task Load Index (TLX).[10] The subject rates the previous task, in this case flight, on the following categories using a 100-point scale: mental demand, physical demand, temporal demand, performance, effort, and frustration. Subjects also perform a weighting procedure, during which they evaluate every pair of subscales (e.g., mental demand vs. temporal demand) and determine which subscale contributed more to the workload of the task. The NASA-TLX then provides a weighted total workload score and scores for the six subscales.

The visual secondary task was developed in house and modeled after the well-validated Multi-Attribute Task Battery-II[26] (see **Appendix F**, found online at https://doi.org/10.3357/amhp.6243sd.2024). The task was presented on a tablet mounted within the cockpit. The task presented two lighted squares on a tan background. One square was green and one square was colorless. At random time intervals, the green square either turned colorless or the colorless square turned red. If these changes were detected, the pilot responded by touching the appropriate square on the tablet within 10 s of the event occurring. Two events occurred at random each minute. Reaction times and accuracy were recorded as outcome measures.

The auditory secondary task was also developed in house (see **Appendix G**, online at https://doi.org/10.3357/amhp.6243sd.2024). This task consisted of radio calls that were delivered via the subjects' headset. The calls consisted of 33% ownship calls which required subjects to respond. An example of such a call is, "Army 0474, traffic is at your 3 o'clock, altitude 020, no factor," where "Army 0474" is the ownship call-sign. An example distractor call is, "Skyhawk 447, climb 050." A member of the research team recorded whether subjects responded to ownship calls and whether the response was appropriate (see Appendix G, online at https://doi.org/10.3357/amhp.6243sd.2024). The outcome measures for this task were number of misunderstood calls and number of inappropriate actions taken.

Data were collected using the U.S. Army Aeromedical Research Laboratory's full motion NUH-60 (Black Hawk) research flight simulator. The NUH-60 consists of a simulator compartment containing a cockpit, instructor/operator station, observer control room observation station, and a six-degree-of-freedom motion system. It is equipped with a 12-channel visual image generator system, 10-ft radius collimated optical display providing a 200° × 45° field of view, and two chin displays. The collimated optical display system consists of seven RGB+infrared light-emitting diode projectors, each providing 2560×1600 pixels resolution for a combined resolution of 1.8 arcminutes/pixel. Two sensor image generator channels are provided for helmet-mounted displays and panel-mounted displays which show infrared, Day TV, and Low Light sensor simulations. The visual system simulates the natural helicopter environment surroundings for day, dusk, or night, and with blowing sand or snow. The data collection system records aircraft/simulator state parameters at a 60-Hz (times per second) capture rate of over 200 variables.

In this study, the following variables collected from the simulator were used for performance measurements: altitude, airspeed, heading, reaction time (seconds) in identifying torque split (measured by turning alert off), glideslope, and localizer during approach. Altitude is measured in feet above sea level, airspeed in knots indicated airspeed (KIAS), and heading is measured in magnetic degrees. The glideslope provides vertical course guidance, whereas the localizer provides lateral course guidance during the approach. Each of these are measured in “dots.” Regarding the glideslope, each dot represents 1.25°, and for the localizer, each dot represents 1.25°.

The active and sham stimulation sessions were accomplished using the HDCStim device (Newronika, Milan, Italy). The HDCStim device is a two-channel device that uses rubber electrodes placed within sponges. The sponge sizes used in this study were 25 cm^2. The HDCStim device is not approved by the Federal Drug Administration for use in the United States for any indication; therefore, all uses of this device under a research protocol in the United States are considered investigational uses and are subject to the U.S. regulations under 21 CFR 812. The HDCStim device was labeled with the following statement: “CAUTION-Investigational Device.”

Procedure

Data collection for this study occurred during the COVID-19 pandemic (November 2020 to May 2021). The research team took additional precautions and procedures to ensure the health and well-being of subjects. All subjects were screened prior to entering the laboratory for any COVID-19 symptoms. Subjects were required to wear cloth masks throughout the duration of the study procedures.

When inside the simulator, members of the research team, including the RPs, wore N-95 masks. There were no noted issues with communication while wearing masks, as supported by a recent evaluation of mask wearing within the aircraft.[5] A summary of the activities that took place throughout each visit are presented in **Fig. 1**.

All tDCS sessions used anodal as the active electrode and cathodal as the reference. tDCS was applied at 2 mA for 20 min total to the right PPC. Sham stimulation was 10% of the duration of each stimulation setting. Sham stimulation is similar to using a placebo control in a pharmacological study. However, since the application of active stimulation produces a physical sensation, typically a tingling sensation,[28] the use of sham stimulation acts as a placebo to maintain blinding. In sham stimulation, the stimulation is turned on briefly then turned off. This allows the subject to experience the tingling sensation

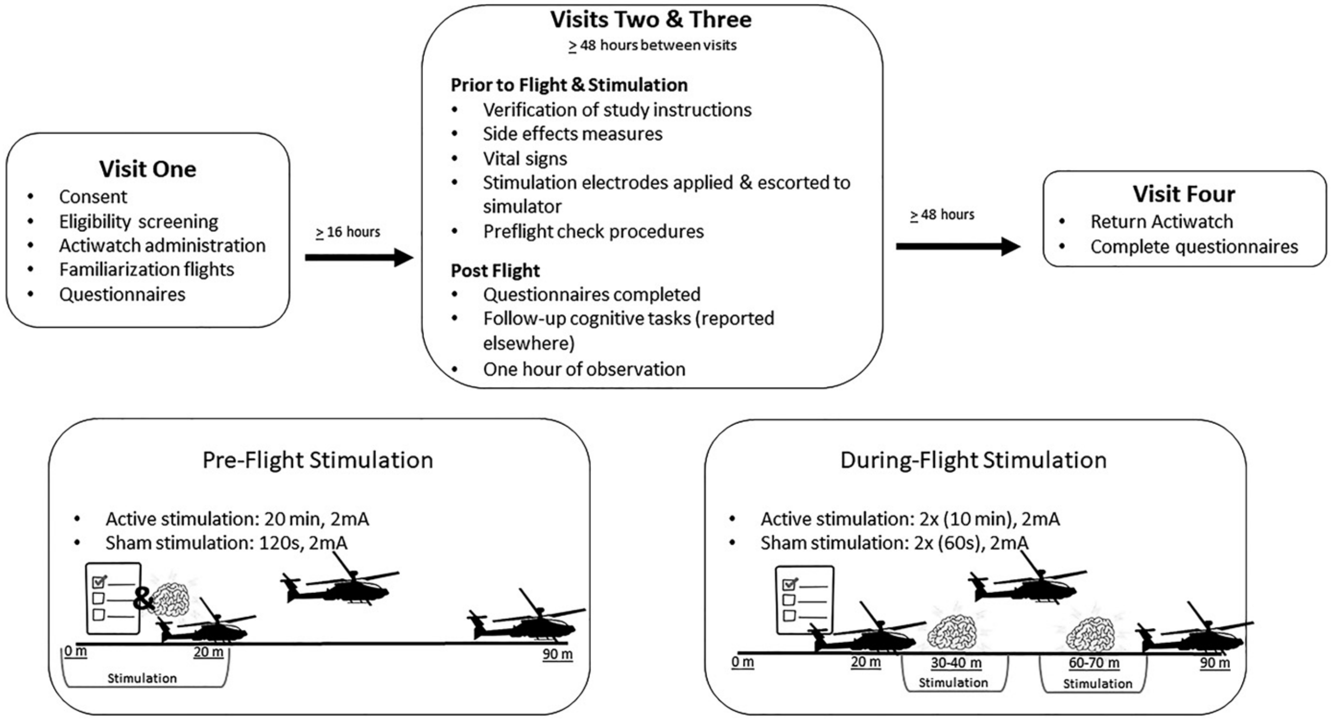

Fig. 1. Summary of study activities.

associated with tDCS application. As most subjects report that they no longer notice the tingling sensation after receiving active stimulation for an extended duration, sham stimulation is accepted in the tDCS research community as a method of blinding. Sham stimulation was set to 10% of the duration of each condition such that those who received stimulation before flight received sham stimulation for 120 s, and the during-flight group received sham stimulation for 60 s each administration. By choosing 10%, each group received the same total duration of sham stimulation in order to emulate the experience of receiving full active stimulation. Condition order was determined by using a web-based random order generator (randomizer.org). This tool produced a table that contained a random order of conditions for each subject.

The rubber anode electrode was placed within a saline-soaked sponge-holding bag and applied to the scalp using the International 10-20 system as a reference. To target the right PPC, the left top of the electrode was placed on the 10-20 electroencephalograph (EEG) system location P4 with the left vertical side aligned to the P4-T6 line. This placement ensured coverage of the temporoparietal junction and inferior parietal lobe that make up the target regions of the PPC.[25] The cathode (5 × 5-cm saline-soaked reference electrode) was centered over the contralateral supraorbital region corresponding to 10-20 EEG system location FP1 (see **Fig. 2**) and was prepared using the same methods as anode. The electrodes were secured in place using a combination of bands made of rubber and Coban wrap (see **Fig. 3**). The sham-stimulation was delivered at the same timepoints as the active stimulation. The prior-to-flight group received the full 20 min of stimulation (or 120 s abbreviated sham stimulation) during the completion of the preflight startup procedures within the simulator. The during-flight group received the first 10 min of stimulation (or 60 s abbreviated sham stimulation) starting at 30 min into the flight, and the second 10 min (or 60 s abbreviated sham stimulation) starting at 60 min into the flight.

The flight scenarios used were designed by RPs assigned to the laboratory. The scenarios lasted approximately 90 min and the difficulty levels of the scenarios were comparable. The flight path was a familiar path to aviators recruited from the area (Cairns Army Airbase, AL, to Montgomery, AL, and vice versa) and featured good weather conditions (e.g., clear sky, minimal wind or turbulence). The intention of the scenario was to create a vigilant state. An RP sat in the cockpit with the subject during the flights. The RPs' role during the flights was to instruct the subjects on the route to be flown and provide instruction regarding maneuvers performed. As such, the RP played the role of a copilot, performing activities such as contacting the tower on approach. The RPs were instructed by the study primary investigator to avoid engaging in any conversational topics with the subjects, as doing so would present a distraction.

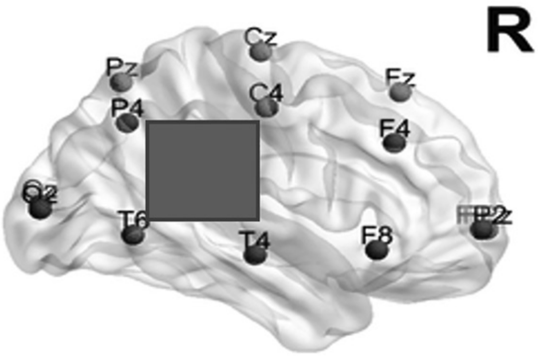

Fig. 2. Placement of anodal electrode in reference to the 10-20 system.


[redacted]

Fig. 3. Example of electrode placements on mock participant.

Two secondary tasks were present throughout the en route portions of the flights: radio calls and a visual task. Radio calls occurred throughout the en route portion of the flight with a 33% ownship rate, with the remaining calls as distractors. The visual task was presented on a tablet mounted within the cockpit and presented events every 2 min. Both tasks are described below. Two emergency events were presented in each flight. The first event was a torque-split emergency around 40 min into the flight which required subjects to acknowledge the emergency by a button press. The second event was presented at the end of each flight. This emergency event required subjects to replan their approach to landing. Introduction of both emergencies were presented to subjects at approximately the same time in all flights. However, there was some variability as presentation depended on both time and location. Thus, subjects who flew faster or slower than the instructed airspeed received the emergencies at slightly different times. However, these differences were minimal. **Table SII** in **Appendix H**

Table I. Primary Flight Outcome Variables: Summary Statistics.

PORTION OF FLIGHT & VARIABLES	PREFLIGHT		DURING FLIGHT	
	SHAM	ACTIVE	SHAM^{+}	ACTIVE
	MEAN (SD)	MEAN (SD)	MEAN (SD)	MEAN (SD)
Pre-Turn				
RMSD Altitude	40.50 (11.20)	36.10 (7.93)	32.00 (5.32)	34.10 (7.82)
RMSD Airspeed	1.10 (0.35)	1.21 (0.31)	1.33 (0.63)	1.26 (0.69)
RMSD Heading	1.20 (0.44)	1.15 (0.56)	1.15 (0.45)	1.06 (0.64)
Torque Split ID (s)	193.00 (103.00)	199.00 (89.70)	215.00 (63.00)	207.00 (105.00)
Post-Turn				
RMSD Altitude	41.90 (10.20)	39.40 (7.99)	42.30 (13.60)	37.70 (8.94)
RMSD Airspeed	1.04 (0.33)	1.26 (0.56)	1.50 (0.94)	1.42 (1.08)
RMSD Heading	1.14 (0.75)	0.99 (0.51)	1.57 (1.22)	1.73 (1.49)
Approach				
*Glideslope	0.13 (0.10)	0.15^{b} (0.13)	0.17^{a} (0.15)	0.05^{a,b} (0.02)
*Localizer	0.13 (0.14)	0.17^{c} (0.09)	0.09 (0.08)	0.07^{c} (0.06)

$^{+}$Missing one participant in During Flight group sham stimulation data due to recording error (no flight data were recorded). *Missing one participant's data due to recording error in sham condition in the Preflight Group. Means with the same superscript (e.g., ^{a}) differ statistically at $P < 0.05$.

(located online at https://doi.org/10.3357/amhp.6243sd.2024) summarizes the flights, including the presentation of secondary tasks and performance variables measured.

The tasks for the two flights were the same, with the flight path changing such that during one flight subjects flew from Cairns to Montgomery, and during the other flight condition flew from Montgomery to Cairns. The starting point for each flight was counterbalanced among subjects. Each flight also included completion of aircraft start-up procedures, lasting approximately 20 min. Subjects were first exposed to these flight scenarios during the experimental procedures. The variables measured from the primary flight tasks included root-mean-squared-deviation (RMSD) from the instructed parameter. Instructed parameters included altitude, heading, and airspeed. For example, to measure performance during the preturn straight and level en route task, the RMSD from the instructed heading of 270°, instructed altitude of 4000 mean sea level (MSL), and instructed airspeed of 110 KIAS were summarized.

All hand-entered data were double-checked for accuracy using a 10% random sample validation check by a team member who did not originally enter the data. Prior to analyses, all electronically recorded data were inspected for any impossible values or output errors. Distributions of all performance (flight, secondary tasks, cognitive tasks) and questionnaires were evaluated for normality and inspected for outliers exceeding three standard deviations from the mean (no outliers were identified). All analyses were completed using R Studio, version 4.1.2, and SPSS, version 25.

Prior to analyzing the performance data, the NASA TLX scores were examined to ensure there were no significant differences in ratings between the two flights (i.e., both flights had similar levels of difficulty). Using paired samples t-tests, no significant differences were found between the two flights on NASA-TLX ratings [$t(21) = -1.78$, $P = 0.09$]. Subjects rated overall workload for flights starting at Cairns (M = 44.80, SD = 14.00) similarly to those starting at Montgomery (M = 49.00, SD = 15.80).

RESULTS

To address the first hypothesis (active stimulation compared to sham stimulation will improve aviator performance), t-tests were performed to evaluate whether performance on the primary and secondary flight tasks were impacted by the application of active tDCS. Specifically, paired samples t-tests compared performance within groups between the sham and active stimulation conditions to determine whether there was an effect of stimulation on performance.

Among the primary flight outcome measures, a significant difference was found between sham and active stimulation conditions for glideslope values [$t(10) = -2.57$, $P = 0.028$, $d = 1.50$] within the during-flight group only. Subjects within the during-flight group demonstrated significantly improved performance, with glideslope values closer to zero, during the active stimulation condition compared to the sham stimulation condition. Descriptive statistics for all outcome measures are provided in **Table I**.

There were no statistically significant differences found in the secondary performance measures between sham and active stimulation conditions. **Table II** summarizes the outcome measures.

To address the second hypothesis (application of tDCS during flight will result in greater performance improvements compared to tDCS before flight), t-tests were performed to evaluate whether performance on the primary and secondary flight tasks were impacted by the timing of tDCS. Specifically, independent samples t-tests were performed between groups on the active stimulation conditions to determine whether there was an effect of the timing of stimulation on performance.

Statistically significant differences were noted for the approach metrics only. Both glideslope and localizer values were statistically different between groups [$t(9.33) = 2.49$, $P = 0.033$, $d = 1.62$; $t\ (15.46) = 2.92$, $P = 0.010$, $d = 1.50$, respectively]. In both cases, those who received stimulation during-flight had values closer to zero, indicating improved performance. Descriptive statistics for all measures are reported in Table I.

Table II. Secondary Flight Outcome Variables: Summary Statistics.

TASK & VARIABLE	PREFLIGHT SHAM MEAN (SD)	PREFLIGHT ACTIVE MEAN (SD)	DURING FLIGHT SHAM MEAN (SD)	DURING FLIGHT ACTIVE MEAN (SD)
Visual Task				
Primary Response RT (ms)	1773.00 (265.00)	1711.00 (220.00)	1731.00 (190.00)	1724.00 (194.00)
Secondary Response RT (ms)	1715.00 (397.00)	1634.00 (244.00)	1603.00 (172.00)	1623.00 (231.00)
Radio Calls				
No. Misunderstood Calls	0.20 (0.42)	1.20 (1.81)	0.17 (0.39)	0.58 (0.90)
No. Inappropriate Actions	0.30 (0.66)	0.30 (0.48)	0.42 (0.70)	0.33 (0.56)

Given the similarity in flights performed under each stimulation mode, order effects were also examined to determine whether familiarity with the flight scenario influenced performance. Only approach data were evaluated, as this was the only outcome measure to achieve statistical significance. Paired-samples *t*-tests were used to compare visit one data with visit two data for each glideslope and localizer values. Data were collapsed across groups and no significant differences were found between sessions for glideslope [$t(30.93) = 1.46$, $P = 0.16$] or localizer [$t(32.45) = 0.80$, $P = 0.16$]. Descriptive statistics are reported in **Table III**.

There were no statistically significant differences between groups on the secondary outcome measures. Descriptive statistics are reported in Table II.

The frequency of reported side effect symptoms are summarized in **Table IV**. No subjects reported a symptom severity rating above a five, which would have required an evaluation by the study physician. In addition to the ratings, the most frequent verbal comments from subjects while receiving stimulation included the experience of "itching," a "metallic taste," and "distracting." Additionally, some subjects commented on not noticing when the stimulation was applied.

The frequency of responses to whether subjects thought they received active stimulation were collapsed across groups. When receiving sham stimulation, 52.38% incorrectly answered "yes," to the statement, "Do you think that you received active stimulation during your participation today?" Regarding when active stimulation was applied, only 31.82% correctly answer "yes" to the previous statement. The frequency of responses to usability items are reported in **Table V**.

DISCUSSION

The aim of the current study was to evaluate whether tDCS can maintain or improve aviator performance during simulated flight. A secondary aim was to evaluate the effects of the timing of stimulation delivery. Two hypotheses were evaluated in support of these aims. In addition, we evaluated end-user perspectives of this type of technology for enhancement purposes.

The first hypothesis (active stimulation compared to sham stimulation will improve aviator performance) was partially supported by the data. A statistically significant difference was found between stimulation conditions (sham and active) within the during-flight group for glideslope values during the approach. Subjects within this group had improved performance during the active stimulation condition. It is notable that this difference between stimulation conditions only became apparent during the approach phase of flight (note, the during-flight group received the second dose of stimulation prior to the approach phase beginning). This may be explained by the design of our flight scenarios. In particular, our flights were designed such that the en route portion of the flight had very low task demands and that an unexpected event occurred during the approach. The presentation of an unexpected event that required subjects to react and replan likely required them to recruit (or reallocate) additional cognitive resources in response to the change in task demands. It is possible that applying active tDCS during the flight, prior to this event, likely aided the subject in recruiting, or reallocating, those cognitive resources. In particular, the timing of the delivery of the in-flight stimulation was chosen to align with the timeframe when vigilance decrement typically occurs (20–30 min into a vigilance task[21]).

The second hypothesis (application of tDCS during flight will results in greater performance improvements compared to tDCS before flight) similarly received partial support from the data. Subjects in the during-flight group showed improved performance on the glideslope metrics compared to the prior-to-flight group. This finding is likely related to the mechanisms by which tDCS works. Specifically, much of the literature surrounding tDCS indicates that tDCS has the greatest effects when applied during a task. It has been speculated that in order for tDCS to have an effect on the behavior of interest, the brain regions responsible for that behavior, which are also targeted by

Table III. Order Effects Summary Statistics.

PORTION OF FLIGHT & VARIABLE	PREFLIGHT STIMULATION 1 MEAN (SD)	PREFLIGHT STIMULATION 2 MEAN (SD)	DURING FLIGHT STIMULATION 1 MEAN (SD)	DURING FLIGHT STIMULATION 2 MEAN (SD)
Approach				
Glideslope	0.186 (0.109)	0.102 (0.107)	0.12 (0.156)	0.094 (0.086)
Localizer	0.196 (0.127)	0.104 (0.093)	0.057 (0.05)	0.091 (0.084)

Table IV. Responses to Post-Stimulation Symptoms Questionnaire.

	SHAM			ACTIVE		
ITEM	FREQUENCY OF POSITIVE RESPONSE	MEAN SEVERITY RATING (SD)	MEAN TIME (MIN) OF ONSET^{+} (SD)	FREQUENCY OF POSITIVE RESPONSE	MEAN SEVERITY RATING (SD)	MEAN TIME (MIN) OF ONSET^{+} (SD)
Nervousness or Anxiety	1	1.00 (NA)	2.00 (NA)	3	2.00 (0.00)	60.00 (52.00)
Acute Mood Change	1	2.00 (NA)	30.00 (NA)	1	3.00 (NA)	30.00 (NA)
Headache	4	1.75 (0.50)	23.80 (17.00)	10	1.40 (0.97)	61.50 (52.70)
Nausea	0	–	–	0	–	–
Neck Pain	0	–	–	2	2.50 (0.71)	127.00 (90.00)
Increased Heart Rate*	1	3 (NA)	30.00 (NA)	1	3 (NA)	30.00 (NA)
Back Pain*	2**	3 (0.00)	700 (0.00)	4	2 (0.82)	260.00 (164.00)
Blurred Vision	0	–	–	0	–	–
Scalp Irritation	0	–	–	2	2.00 (1.41)	37.50 (10.60)
Tingling	1	3.00 (NA)	60.00 (NA)	6	1.83 (1.17)	47.00 (43.20)
Itching	3	1.67 (1.16)	21.00 (15.60)	5	2.00 (0.71)	56.00 (41.60)
Burning Sensation	1	2 (NA)	20.00 (NA)	2	3.50 (0.71)	20.00 (14.10)
Hot Flush*	0	–	–	0	–	–
Dizziness*	0	–	–	0	–	–
Fatigue	0	–	–	1	3.00 (NA)	30.00 (NA)
Difficulty Concentrating	0	–	–	1	2.00 (NA)	30.00 (NA)

*Pseudo-items. $^{+}$Mean Time of Onset are reported in minutes. Time of onset was defined as the number of minutes since the symptom began. **Backpain is a common experience in rotary-wing aviators.

tDCS, must be actively engaged. Thus, our finding that the group who received stimulation during flight showed improved performance is in line with the current understanding of how tDCS works.

Of note, however, is that only the metrics related to the approach performance improved. None of the other metrics measured during the flight showed any sort of difference between groups, nor between active and sham stimulation. This null finding is most likely related to the tasks that were being performed, which leads to why our second hypothesis was only partially supported. The flight was designed to be relatively minimal workload, but still requiring the aviators to stay engaged (e.g., with the use of turns spaced throughout the flight). However, the unexpected emergency event (introduction of inadvertent instrument meteorological conditions) during the approach phase was introduced to create a sudden increase in workload. Thus, the null findings of the other performance metrics during flight are as expected. Demonstrating that the application of tDCS aided in performance when the unexpected emergency event occurred is indicative of tDCS playing a role in reallocating the cognitive resources needed to respond to that event. However, given our findings, we cannot fully draw conclusions regarding the utility of stimulation in all flight scenarios. For example, a different flight scenario that was more demanding earlier on in the flight may have benefited from stimulation prior to the flight. This requires additional research across a range of flight scenarios and tasks to determine when stimulation has the greatest utility. It is likely that tDCS parameters (such as target brain region and timing of delivery) are flight mission specific.

Table V. Usability of tDCS.

ITEM	STRONGLY DISAGREE *N* (%)	DISAGREE *N* (%)	UNDECIDED *N* (%)	AGREE *N* (%)	STRONGLY AGREE *N* (%)
I could easily learn how to use tDCS.	–	–	6 (27%)	14 (64%)	2 (9.1%)
It is a good idea for soldiers to use tDCS as a cognitive enhancement tool in operational environments.	–	3 (14%)	14 (64%)	5 (23%)	–
Most of my fellow soldiers will welcome the fact that I use tDCS as a cognitive enhancement tool.	1 (4.5%)	4 (18%)	12 (55%)	5 (23%)	–
The military will encourage the use of tDCS as a cognitive enhancement tool.	–	4 (18%)	12 (55%)	6 (27%)	–
I feel comfortable with using tDCS in an operational environment.	1 (4.5%)	4 (18%)	9 (41%)	7 (32%)	1 (4.5%)
I intend to use tDCS as a cognitive enhancement tool in operational settings if/when the military makes it available to soldiers.	1 (4.5%)	2 (9.1%)	9 (41%)	10 (46%)	–

Regarding the blinding efficacy with the sham condition used, our results suggest subjects were sufficiently blinded. For the sham conditions, only 52% correctly speculated they were receiving the sham stimulation. Alternatively, during the active conditions, only 32% correctly identified the condition. In a recent study, 52.78% of subjects were able to correctly guess allocation to sham and active conditions.[16] Thus, our findings are in line with the current rate of blinding efficacy and better for the active conditions given that a smaller percentage of subjects correctly identified which condition they were experiencing. The finding that only one-third of subjects correctly guessed active stimulation in comparison to recent studies where 52.78% of subjects correctly guessed active stimulation may be due to the nature of the tasks subjects were engaged in. While receiving stimulation, subjects were either actively engaged in the preflight checklist procedures or actively flying the aircraft. Thus, they may have been distracted from noticing the presence of the stimulation, which was stated by some of our subjects.

Survey items to assess end-user acceptance revealed subjects were generally open to the concept of tDCS used in an operational setting. Regarding whether subjects would use tDCS as a cognitive enhancement tool, should the military make it available to soldiers, nearly half (46%) indicated agreement, while 41% remained undecided, and approximately 13% disagreed. Although this was a small sample, this provides some indication to one question often unanswered in enhancement literature—would they actually want to use it? Results found here provide an initial view into whether military members would be open to its use. However, with 41% remaining undecided, further research would be needed to truly evaluate the end-user's acceptance. Additionally, this small sample is by no means representative of all soldiers. Further, it may be that subjects who were in the study were biased to agree with its use for cognitive enhancement simply due to their participation. For a more accurate assessment of user acceptance, a secondary study should be completed using a use-case scenario presentation and/or an educational effort to ascertain acceptance. For example, subjects within the current study were only informed of the risks of tDCS during the consent process. Additionally, we did not go into in-depth details regarding how tDCS works to impact brain activity. Thus, different results may be found if a larger sample were queried and were provided further details on the technology.

The study was not without limitations. One considerable limitation was the use of a single-blind design. However, the reasoning for this was due to safety concerns, with this study being one of the first, to the authors' knowledge, using tDCS within a full-motion flight simulator. Future work should consider replicating these findings using a double-blind approach. Another limitation of the study is the potential for order effects given we used the same emergencies in both flights. It is likely subjects anticipated the presence of emergencies in the second flight. However, our analyses of order effects suggested this was not the case.

The results presented here have several practical implications. First, the finding that tDCS applied during flight resulted in improved performance compared to prior to flight suggests there are bounds within which tDCS can be effective for operational use. This finding is currently limited to the conditions under which we tested and would require evaluation of its use in other flight scenarios, and a larger sample, to make these findings more generalizable. Given the current state of the technology, it is not feasible to apply tDCS during a flight. However, sensor technology is rapidly changing and becoming more wearable. Thus, the findings suggest that, given current technology, tDCS may only be feasible for nonflight activities, such as unmanned aerial systems operators or air traffic controllers. However, this also points to the need to further evaluate the safety constraints with which tDCS can be used. If application of tDCS during flight tasks can significantly improve performance, it is worthwhile to evaluate the safety of applying them during such tasks.

ACKNOWLEDGMENTS

The views expressed are those of the authors and do not reflect the official guidance or position of the U.S. Government, the Department of Defense, or the U.S. Army.

Portions of these findings were presented orally at the International Brain Stimulation conference (December 2021). These findings are also reported within a technical report, as cited in the manuscript.

Financial Disclosure Statement: The authors have no conflicts of interest to disclose.

Authors and Affiliations: Kathryn A. Feltman, Ph.D., Research Psychologist, and Amanda M. Kelley, M.S., Ph.D., Research Psychologist, U.S. Army Aeromedical Research Laboratory, Fort Novosel, AL, United States.

REFERENCES

1. American Psychiatric Association. Diagnostic and statistical manual of mental health disorders: DSM-IV-TR. Washington (DC): American Psychiatric Association; 2000.
2. Beck AT, Steer RA, Brown GK. Manual for the Beck Depression Inventory-II. San Antonio (TX): Psychological Corporation; 1996.
3. Bikson M, Rahman A. Origins of specificity during tDCS: anatomical, activity-selective, and input-bias mechanisms. Front Hum Neurosci. 2013; 7:688.
4. Buchanan DM, Bogdanowicz T, Khanna N, Lockman-Dufour G, Robaey P, D'Anguili A. Systematic review on the safety and tolerability of transcranial current stimulation in children and adolescents. Brain Sci. 2021; 11(2):212.
5. Cave KM, Kelley AM, Feltman KA, Gerstner J, Stewart J, Crowley JS. Assessment of aircrew performance and safety while using protective masks: response to coronavirus disease. Aerosp Med Hum Perform. 2021; 92(4):274–280.
6. Clark I, Landolt HP. Coffee, caffeine, and sleep: a systematic review of epidemiological studies and randomized controlled trials. Sleep Med Rev. 2017; 31:70–78.
7. Drake C, Roehrs T, Shambroom J, Roth T. Caffeine effects on sleep taken 0, 3, or 6 hours before going to bed. J Clin Sleep Med. 2013; 9(11): 1195–1200.
8. Duffy MJ, Feltman KA. A systematic literature review of operator state detection using physiological measures. Fort Rucker (AL): U.S. Army

Aeromedical Research Laboratory; 2022. Report No.: USAARL-TECH-TR–2023-11.

9. Feltman KA, Mathews C, Mackie R, Morabito CP, Kelley AM. Transcranial electrical stimulation to sustain aviator performance: the effects of timing of stimulation and individual differences. Fort Rucker (AL): U.S. Aeromedical Research Laboratory; 2021. Report No.: USAARL-TECH-FR-2021-42.
10. Hart SG, Staveland LE. Development of NASA-TLX (Task Load Index): results of empirical and theoretical research. Advances in psychology. 1988; 52:139–183.
11. Hashemian SM, Farhadi T. A review on modafinil: the characteristics, function, and use in critical care. J Drug Assess. 2020; 9(1):82–86.
12. Karthikeyan R, Smoot MR, Mehta RK. Anodal tDCS augments and preserves working memory beyond time-on-task deficits. Sci Rep. 2021; 11(1):19134.
13. Kelley AM, Webb CM, Athy JR, Ley S, Gaydos S. Cognition enhancement by modafinil: a meta-analysis. Aviat Space Environ Med. 2012; 83(7): 685–690.
14. Kessler RC, Adler L, Ames M, Demler O, Faraone S, et al. The World Health Organization Adult ADHD Self-Report Scale (ASRS): a short screening scale for use in the general population. Psychol Med. 2005; 35(2):245–256.
15. Langner R, Eickhoff SB. Sustaining attention to simple tasks: a meta-analytic review of the neural mechanisms of vigilant attention. Psychol Bull. 2013; 139(4):870–900.
16. Lema A, Carvalho S, Fregni F, Gonçalves ÓF, Leite J. The effects of direct current stimulation and random noise stimulation on attention networks. Sci Rep. 2021; 11(1):6201.
17. Li LM, Leech R, Scott G, Malhotra P, Seemungal B, Sharp DJ. The effect of oppositional parietal transcranial direct current stimulation on lateralized brain functions. Eur J Neurosci. 2015; 42(11):2904–2914.
18. Lo OY, van Donkelaar P, Chou L. Effects of transcranial direct current stimulation over right posterior parietal cortex on attention function in healthy young adults. Eur J Neurosci. 2019; 49(12):1623–1631.
19. Nelson JT, McKinley RA, Golob EJ, Warm JS, Parasuraman R. Enhancing vigilance in operators with prefrontal cortex transcranial direct current stimulation (tDCS). Neuroimage. 2014; 85(Pt 3):909–917.
20. Parasuraman R, Molloy R, Singh IL. Performance consequences of automation-induced 'complacency'. Int J Aviat Psychol. 1993; 3(1):1–23.
21. Pattyn N, Neyt X, Henderickx D, Soetens E. Psychophysiological investigation of vigilance decrement: boredom or cognitive fatigue? Physiol Behav. 2008; 93(1–2):369–378.
22. Pilloni G, Vogel-Eyny A, Lustberg M, Best P, Malik M, et al. Tolerability and feasibility of at-home remotely supervised transcranial direct current stimulation (RS-tDCS): single-center evidence from 6,779 sessions. Brain Stimul. 2022; 15(3):707–716.
23. Pisoni A, Mattavelli G, Papagno C, Rosanova M, Casali AG, Lauro LJR. Cognitive enhancement induced by anodal tDCS drives circuit-specific cortical plasticity. Cereb Cortex. 2018; 28(4):1132–1140.
24. Reteig LC, Talsma LJ, Schouwenburg MR, Slagter HA. Transcranial electrical stimulation as a tool to enhance attention. J Cogn Enhanc. 2017; 1(1):10–25.
25. Rojas GM, Alvarez C, Montoya CE, de la Iglesia-Vayá M, Cisternas JE, Gálvez M. Study of resting-state functional connectivity networks using EEG electrodes position as seed. Front Neurosci. 2018; 12:235.
26. Santiago-Espada Y, Myer RR, Latorella KA, Comstock JR. The Multi-Attribute Task Battery II (MATB-II) software for human performance and workload research: a user's guide. Hampton (VA): Langley Research Center, National Aeronautics and Space Administration; 2011.
27. Snyder LH, Batista AP, Anderson RA. Intention-related activity in the posterior parietal cortex: a review. Vision Res. 2000; 40(10-12): 1433–1441.
28. Sudbrack-Oliveira P, Razza LB, Brunoni AR. Non-invasive cortical stimulation: transcranial direct current stimulation (tDCS). Int Rev Neurobiol. 2021; 159:1–22.
29. Thair H, Holloway AL, Newport R, Smith AD. Transcranial direct current stimulation (tDCS): a beginner's guide foor design and implementation. Front Neurosci. 2017; 11:641.
30. Thakral PP, Slotnick SD. The role of parietal cortex during sustained visual spatial attention. Brain Res. 2009; 1302:157–166.
31. Vergallito A, Feroldi S, Pisoni A, Lauro LJR. Inter-individual variability in tDCS effects: a narrative review on the contribution of stable, variable, and contextual factors. Brain Sci. 2022; 12(5):522.
32. Warm JS, Parasuraman R, Matthews G. Vigilance requires hard mental work and is stressful. Hum Factors. 2008; 50(3):433–441.
33. Weller S, Nitsche MA, Plewnia C. Enhancing cognitive control training with transcranial direct current stimulation: a systematic parameter study. Brain Stimul. 2020; 13(5):1358–1369.

U.S. ARMY AEROMEDICAL RESEARCH LABORATORY

FORT RUCKER, ALABAMA

Optimizing

HUMAN PROTECTION
AND PERFORMANCE

since 1962

U.S. ARMY

FCC

MRDC