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Evaluation of a Novel Wearable EEG/EOG Sensor for Real-Time Operator State Monitoring

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14. ABSTRACT
Real-time monitoring of pilots' cognitive state using psychophysiological measurements is critical for aviation safety. However, current laboratory-grade electroencephalography (EEG) devices require extensive wired electrodes and setup, limiting feasibility for in-flight use. This study evaluated wireless prototypes consisting of a four channel EEG and two channel electrooculography (EOG) forehead sensor to assess their potential to monitor cognitive state during flight. The sensor utilizes flexible dry electrodes and minimal setup. Comparisons to laboratory EEG were done across varying workload tasks. However, signal contamination at 30 Hertz (Hz), potentially from hardware issues, prevented EEG data analysis. Enhanced durability is critical for unreliable environmental settings along with pre-deployment functionality checks. Despite current issues, the compact sensor shows promise if functioning reliably. Considerable further development and rigorous in-flight testing is required before adoption. With refinements ensuring robust data quality, the sensor concept holds promise for objectively monitoring hazardous states like excessive workload and fatigue in-flight. Once thoroughly validated for flight conditions, similar forehead prototypes may someday fill the pressing need for real-time mental state monitoring to enhance aviation safety.

15. SUBJECT TERMS
electroencephalography (EEG), operator state monitoring (OSM), mental workload

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Summary

Real-time monitoring of an operator's cognitive state through psychophysiological indices is critical for aviation safety and performance. Currently, traditional laboratory-grade electroencephalography (EEG) devices requiring extensive wired electrodes and time-intensive applications limit the feasibility of pilot monitoring during flight. This study evaluated two early phase developmental prototypes that consisted of a wireless four-channel EEG and a two-channel electrooculography (EOG) forehead sensor prototype to assess their future potential for monitoring pilots' cognitive states during flight. The sensor utilizes flexible dry electrodes and minimal setup for data collection. Comparisons to a laboratory-grade EEG device were conducted across tasks inducing varying mental workloads. However, pronounced noise at 30 Hertz (Hz) across channels suggests significant environmental signal contamination, potentially due to hardware issues, given participants' consistent power spectral density profiles. This noise within the data prevented meaningful analysis of the EEG data. Enhanced durability is critical for unreliable field settings and functionality checks before deployment. Despite these issues, this sensor's compact design shows promise if functioning reliably. Considerable development and rigorous testing under sustained aviation conditions will be required before adoption. With refinements ensuring robust data quality, the sensor concept holds promise for objectively monitoring hazardous states like excessive workload and fatigue. Once matured and thoroughly validated for unforgiving flight contexts, similar forehead EEG/EOG prototypes may someday fill a pressing need for mental state monitoring in next-generation aircraft.

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We also would like to thank our collaborators, the Nanshu Lu laboratory group at the University of Texas at Austin, for e-tattoo prototype development and allowing for USAARL to evaluate the device.

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Introduction

Advanced aircraft technologies substantially raise the cognitive demands placed on pilots. Features like increased automation, high speeds, expanded reconnaissance capabilities, and longer flights significantly increase the mental workload of aviators (Caldwell, 2005). If overwhelmed by these escalating demands, risks of fatigue, attention lapses, and other hazardous mental states increase as well, endangering aviation safety. Thus, real-time monitoring of cognitive workload, fatigue levels, and overall mental state through lightweight wearable sensors could enable critical, timely interventions when dangerous conditions occur (Kale et al., 2020). While monitoring operator functional state has long aimed to optimize human-machine system performance and safety, traditional measures rely heavily on subjective self-report techniques. However, these retrospective questionnaires have significant limitations in accuracy, reliability, and actionability (Grier et al., 2003). Emerging psychophysiological measures assessing central and autonomic nervous system dynamics provide more objective, temporally sensitive biomarkers of real-time cognitive, affective, and physical states (Durantin et al., 2014). For example, electroencephalography (EEG) is a robust indicator of mental workload, with recordings reliably demonstrating changes in theta spectral power between high and low task loads (Hankins & Wilson, 1998; Borghini et al., 2014). Likewise, electrooculography (EOG) sensitively measures fatigue during prolonged vigilance tasks through changes in eye blink rates and dynamics (Di Flumeri et al., 2018).

While laboratory-grade EEG equipment has monitored pilot cognition in simulators, extensive wired electrodes, and time-intensive application limit feasibility for in-flight settings (Dussault et al., 2004; Rashid et al., 2020). Recent advances in wearable sensors aim to address these barriers but still require validation. EEG recordings have demonstrated capability as robust indicators of mental workload, reliably showing changes in theta power between high and low task loads (Hankins & Wilson, 1998; Borghini et al., 2014). However, donning cumbersome electrode-capped headsets is impractical for flight, and helmet integration remains challenging. Recent wearable EEG sensors utilizing flexible dry electrodes provide more user-friendly solutions amenable to aviation contexts, though signal quality requires rigorous validation against research-grade systems before adoption. This study evaluated an innovative wireless four-channel EEG plus a two-channel EOG forehead sensor prototype from the University of Texas at Austin, referred to as the 'e-tattoo' device. Using a thin, flexible, printed circuit board with conductive polymer electrodes laminated onto the forehead, this sensor enables unobtrusive EEG and oculometric monitoring. Connecting via Bluetooth to a smartphone application for easy data acquisition, this design has the potential to capture real-time brain activity needed for monitoring the cognitive state of an aviator.

In this study, we compared the prototype e-tattoo device to a laboratory-grade EEG. Comparisons were conducted across two different tasks inducing varying mental workload and fatigue levels. Carefully validating signal fidelity could demonstrate feasibility for practical in-flight monitoring of relevant cognitive states using this wearable approach. Supporting unobtrusive EEG/EOG measurement via this forehead sensor prototype could enable critical, timely interventions guided by objectively assessing hazardous pilot mental states. Demonstrating comparable data quality to standard laboratory equipment would underscore the significant potential benefits of this innovative wearable solution for next-generation aviation safety and beyond.

Methods

Participants

Six Soldiers aged 24-30 years (M = 27, SD = 2.97) took part in the study. Participants provided written informed consent prior to participation. All had normal or corrected-to-normal vision. Three participants participated in the experimental evaluation of the e-tattoo prototype A and all six participated in the experimental evaluation of the e-tattoo prototype B (described further in Equipment and Testing). During the experiments, the participants completed both the psychomotor vigilance task (PVT) and *n*-back task in a counterbalanced, randomized order as both tasks are commonly used to evaluate mental workload. These tasks were chosen to potentially provide insight to different levels of workload for a correlative analysis between workload and EEG signals as research suggests the *n*-back task induces a higher level of workload compared to the PVT.

The PVT requires sustained attention and reaction time by having participants respond to visual stimuli that appear at random intervals (Basner & Dinges, 2011). In contrast, the *n*-back task requires working memory, requiring participants to indicate if the current stimulus matches the one from *n* items earlier. Studies have found the *n*-back induces greater mental workload relative to the simpler PVT. For example, Grier et al. (2003) measured workload using pupil dilation and found significantly higher values during a 3-back test compared to a PVT with matched response rates. Similarly, Ayaz et al. (2012) used functional near infrared spectroscopy and found that a 2-back test produced higher prefrontal cortex activation compared to the PVT, suggesting higher mental workload. The differing cognitive demands of these tasks, with the *n*-back additionally requiring manipulation of remembered information, produces measurable differences in induced workload even when tasks have equivalent motor output. This has implications for assessing operator or system capacity and overload potential.

Subjective workload was captured after each task using the National Aeronautics and Space Administration Task Load Index (NASA TLX), a multidimensional scale assessing mental, physical, and temporal demands, performance, effort, and frustration. Additional measures included a demographic and health questionnaire, the State-Trait Anxiety Inventory (STAI) to assess state and trait anxiety levels, the Beck Depression Inventory (BDI-II) to measure depression symptoms, and the Karolinska Sleepiness Scale (KSS) to evaluate situational sleepiness. See Table 3 for the descriptive statistics. These additional performance metrics provide further insight into cognitive/affective states relevant to operator monitoring. The outcomes of the surveys are further described in the results section.

Equipment and Testing

Prior to application of the e-tattoo device, extensive skin preparation of the face and mastoids was undertaken to help reduce electrical impedance that could interfere with signal quality. The skin surface where the e-tattoo device was to be adhered was first cleaned extensively with isopropyl alcohol wipes to remove oils, cosmetics, dead skin cells, and other impedance-increasing contaminants. After allowing sufficient drying time, an abrasive gel was then gently applied to the areas of adhesion and rubbed in a circular motion using a soft cloth to further exfoliate the stratum corneum outer skin layer. These extensive cleansing and mild abrasion techniques have been demonstrated through impedance testing and signal-to-noise measurements to significantly reduce skin impedance and improve electrode-skin contact, thereby enhancing the signal quality obtained from the flexible and conformal e-tattoo biosensors. The reduction in impedance noise allows detection of finer physiological signals. Following the cleaning and abrasion preparations, the e-tattoo was then successfully adhered to the prepared facial locations with clear adhesive strips, with care taken to avoid entrapment of air bubbles between the skin and sensors.

We tested two different e-tattoo prototypes during the experimentation process. Prototype A contained a larger battery, and after initial testing, the necessity for hardware improvement prompted the development of a second prototype (prototype B) (see Figure 1). Prototype B (University of Texas at Austin [UTA]) contained a four-channel EEG and two-channel EOG setup. EEG was recorded from sites Fp1, Fp2, F7, and F8. The thin-film dry electrodes and a flexible printed circuit board (FPC) can be referred to as an EEG patch. The thin-film dry electrodes were manufactured with biocompatible and conductive polymer: graphite particle deposited polyurethane (G-PU) or poly (3, 4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT: PSS). Such polymers' ultra-thinness, lightweight, and stretchability result in highly skin-conformable dry electrodes, enabling more robust and reliable EEG. The EEG patches do not have Food and Drug Administration clearance or investigational device exemption numbers. The FPC includes light-emitting diodes, integrated circuit chips (e.g., microcontroller, Bluetooth chip, accelerometer, antenna), and a coin cell battery which was placed on the top side of the Tegaderm. The only material in contact with the body was the Tegaderm medical dressing and electrode materials. The EEG patch was laminated on the forehead and paired via Bluetooth with a smartphone with a side-loaded application developed by UTA for the wireless acquisition and display of the biometric data sensed by the patch. A commercial 32-channel EEG amplifier (LiveAmp, Brain Vision) was used as a data acquisition system for EEG signal recording and monitoring. The signal quality was evaluated through a well-known signal-to-noise ratio, and the electrode-skin contact was evaluated by assessing impedance over time.

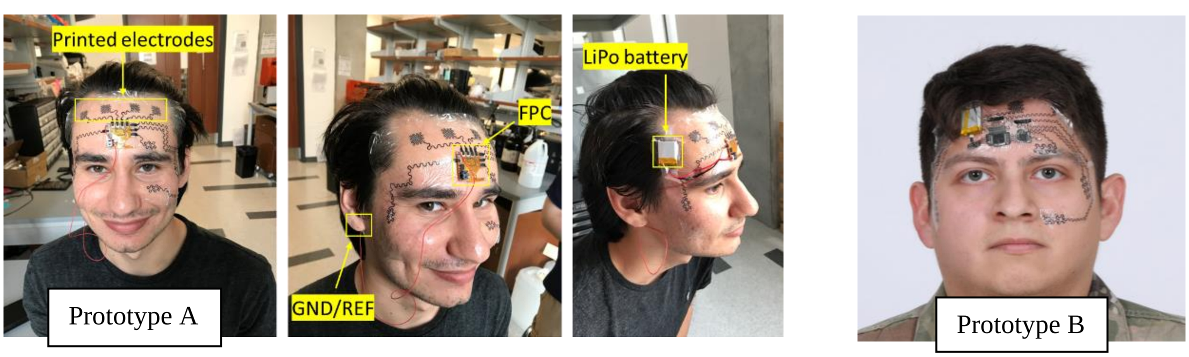

Figure 1. E-tattoo prototype applied on the forehead.

Laboratory-grade EEG data was collected using the Neuroelectrics® Starstim 8 system. The StarStim 8 utilizes a neoprene head cap and channels correspond to scalp locations according to the International 10-20 system (frontal channels: Fp1, Fp2, F7, F3, Fz, F4, F8; central channels: C3, Cz, C4, T3, T4; parietal and occipital channels: P3, POz, Pz, P4, T5, T6, O1, O2). Eight silver-silver chloride (Ag/AgCl) electrodes were placed at anatomical locations closely matching the e-tattoo device electrode locations. Electrodes were placed within the neoprene head cap and filled with conductive gel before data collection. Within the Neuroelectrics Instrument Controller software, a protocol is created to monitor and record the desired configuration of channels. The quality index was monitored to ensure good data quality. EOG data was collected using the reference electrode channels using the Starstim 8 EEG device. EOG assessed vertical eye blink activity by placing pre-gelled 4.5 square centimeter (cm^2) electrodes above and below the left eye.

Results

The present study was designed to compare the EEG data recorded using thin-film dry electrodes (e-tattoo) with a commercially available wearable EEG device (StarStim). Initially, we conducted a power spectral density (PSD) comparison across the entire time series to establish a baseline. This PSD analysis assessed the overall data quality for the entire recording session before delving into more detailed, time-locked single-trial analyses, which could highlight finer data quality differences.

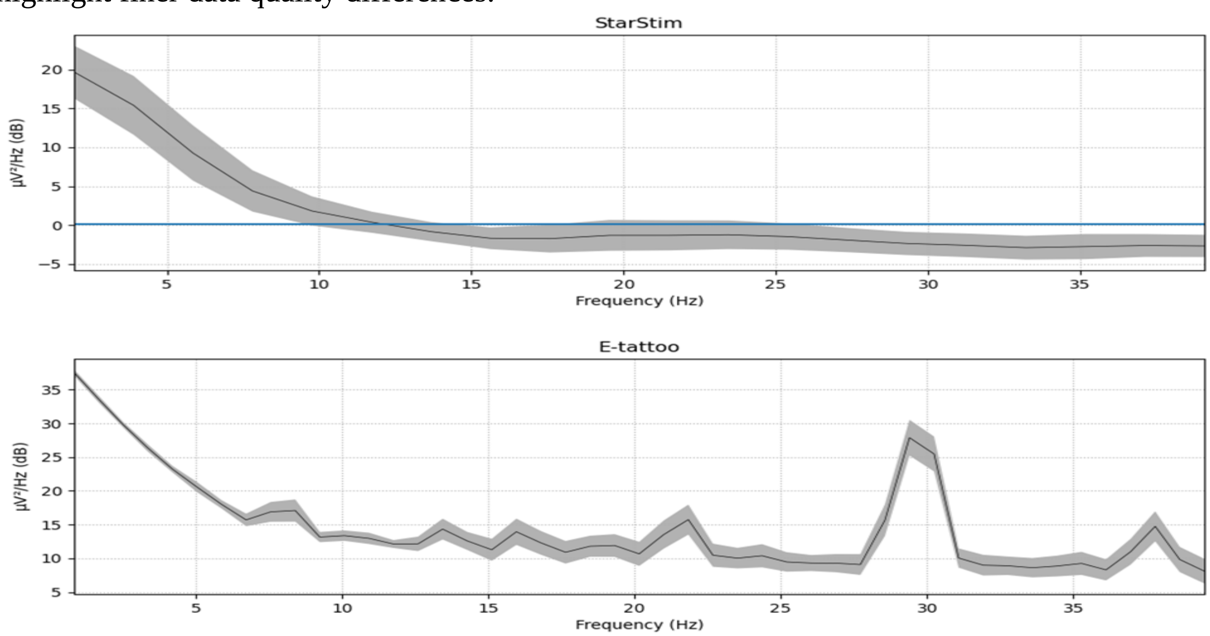

Figure 2. Comparison of the PSD functions for StarStim (top) and e-tattoo (bottom). In both plots, the *x*-axis represents frequency, while the *y*-axis represents the power in decibels (DB) at each frequency.

First, we bandpass filtered the raw signals from both devices, retaining frequencies between 0.1 Hertz (Hz) and 40 Hz, effectively removing the 60 Hz power line noise. Subsequently, we calculated the PSD using the Fast Fourier Transform. Figure 2 depicts the PSD for the StarStim and e-tattoo, where we noticed a significant difference in the PSD functions between the two datasets. Notably, the e-tattoo data exhibited a pronounced PSD at 30 Hz, which was absent in the StarStim data. All participants showed similar PSD curves. Given that 30 Hz is a harmonic frequency of the 60 Hz power line noise, this indicated that the e-tattoo device was picking up environmental noise. To confirm this, we revisited the raw e-tattoo signal (as shown in Figure 3), which displayed strong 30 Hz periodic oscillations, corroborating our PSD findings that the e-tattoo device was indeed capturing environmental power line noise. To further investigate the noise issue, we repeated the PSD analysis, this time applying a band-pass filter to the signal from 0.1 Hz to 100 Hz. This was done to retain the 60 Hz power line noise. As illustrated in Figure 4, a distinct PSD peak is visible at both 60 Hz and its harmonic frequency of 30 and 90 Hz. This power line noise, significantly stronger than any potential EEG signal, rendered any meaningful analysis of the e-tattoo EEG signal impossible. We observed similar results with both prototypes. Therefore, we did not proceed with further analysis to assess the quality of the e-tattoo dataset.

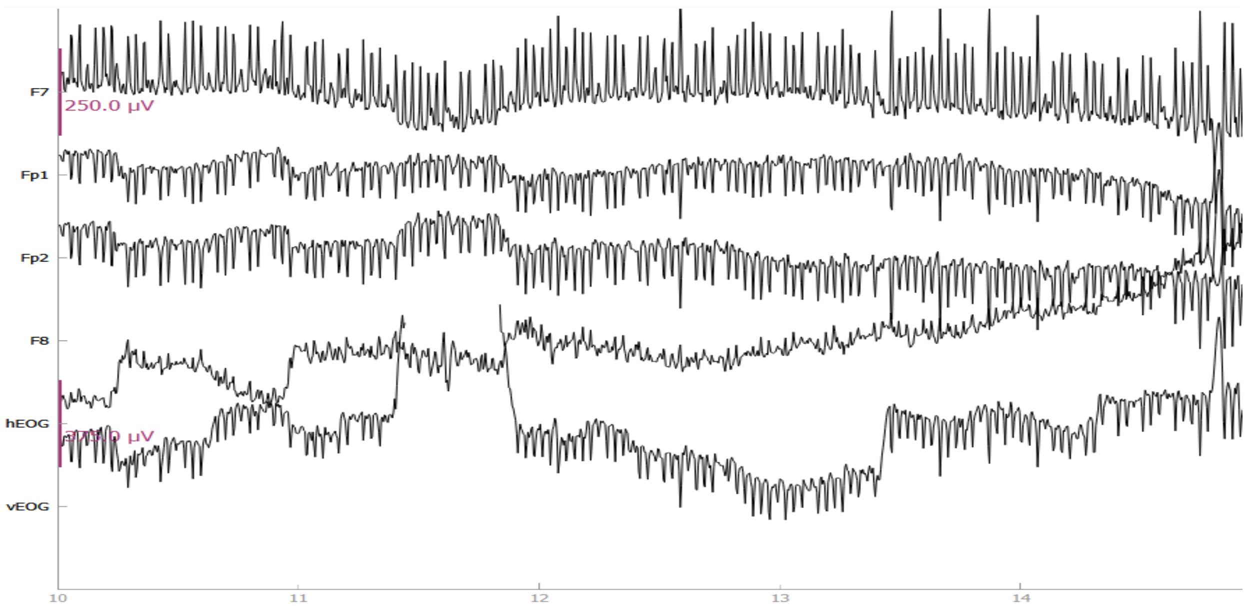

Figure 3. Raw EEG signal recorded using the e-tattoo device. This figure illustrates the raw EEG signal with the *x*-axis indicating time and *y*-axis showing both the EEG channels (F7, Fp1, Fp2, F8) and EOG channels (hEOG, vEOG), with their respective voltage measurements. Notably, there is a prominent periodic oscillation at 30 Hz visible across all channels.

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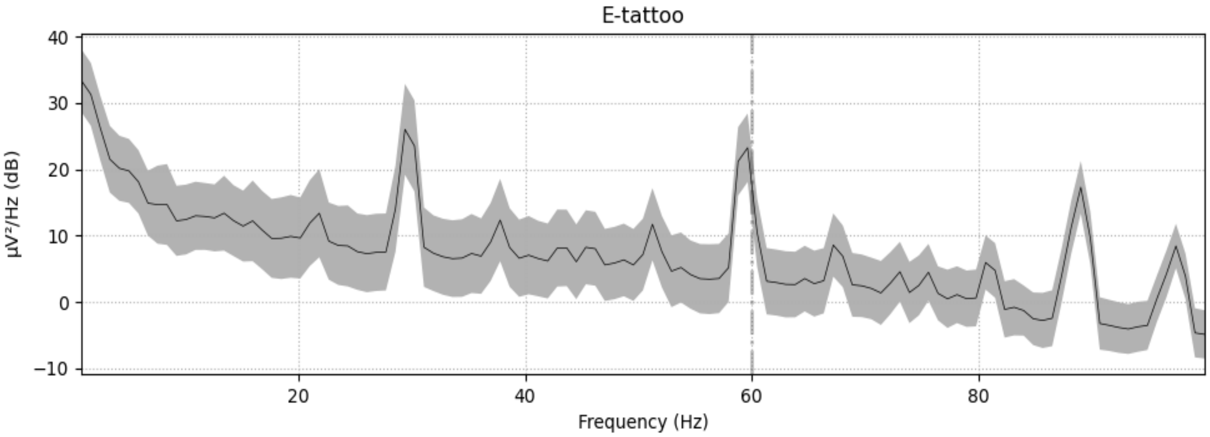

Figure 4. An example of e-tattoo PSD function with band-pass filtering of 0.1 Hz to 100 Hz. The *x*-axis represents frequency, while *y*-axis represents the power in DB at each frequency. The PSD calculated from the e-tattoo signal shows a pronounced peak at 30, 60, and 90 Hz. *Note.* Figures 2-4 are a representative dataset from one participant.

Subjective Workload Ratings

Results from the NASA TLX did indeed indicate that the *n*-back and PVT tasks differed in subjective workload ratings as participants rated the *n*-back as having higher mental, physical, and temporal demands, as well as the task taking more effort to complete and inducing more frustration compared to the PVT.

Table 1. Descriptive Statistics for the *n*-back Task

NASA TLX dimension	*M*	*SD*	Min.	Max.
Mental demand	74.688	22.691	20	95
Physical demand	9.375	12.764	0	35
Temporal demand	69.062	15.939	20	85
Performance	38.75	25.852	5	85
Effort	69.062	10.835	50	90
Frustration	29.062	21.073	0	65

Note. n = 16

Table 2. Descriptive Statistics for the PVT Task

NASA TLX dimension	*M*	*SD*	Min.	Max.
Mental demand	64.375	21.046	20	95
Physical demand	11.875	12.366	0	35
Temporal demand	64.375	25.091	0	95
Performance	27.5	15.492	0	50
Effort	61.562	17.39	25	90
Frustration	26.562	23.994	0	65

Note. Six participants performed three task iterations.

None of the participants scored within the clinical range for depression on the Beck Depression Inventory (BDI) (Beck et al., 1996). Scores on the BDI ranged from 0 to 1 (M = 0.33, SD = 0.5), indicating minimal depression (scores from 0 to 13). For the Karolinska Sleepiness Scale (KSS) ratings, the average value was 3.27 (scores ranged from 1-7.2, SD = 1.88). This indicates that participants, on average, were alert during the study (Miley et al., 2016). The KSS was repeated five times for each participant and average values were calculated. The STAI contains 40 self-report questions rated on a 1-4 Likert scale (Kayikcioglu et al., 2017). It can be divided into state anxiety (STAI S), which assesses stress-induced anxiety, and trait anxiety (STAI T), which measures an individual's general tendency for anxiety. STAI scores between 20-37 indicate no or low anxiety, which is what was observed in our experiments (see Table 3 below).

Table 3. Descriptive Statistics for Questionnaires

Questionnaire	***M***	***SD***	**Min.**	**Max.**
BDI	0.33	0.50	0	1
KSS	3.27	1.88	1	7.2
STAI S-Anxiety	24.11	4.17	20	32
STAI T-Anxiety	24.78	5.61	20	32

Note. n = 9

Discussion

As advanced aircraft technologies place new cognitive demands on pilots, real-time monitoring of mental states through wearable sensors could enable timely interventions when hazardous states like excessive workload or fatigue occur. EEG and EOG have been validated for monitoring cognitive workload and fatigue, but laboratory-grade equipment has poor feasibility for aviation contexts. Recent wearable EEG sensors provide more practical solutions but require signal quality validation before adoption. This study evaluated a wireless four-channel EEG plus a two-channel EOG forehead sensor prototype (e-tattoo) for monitoring brain activity levels. The sensor has the potential to balance data quality and usability through flexible dry electrodes and minimal setup. However, a comparison to a laboratory-grade EEG device showed that the forehead sensor data was significantly contaminated by environmental noise, indicated by a pronounced 30 Hz peak across channels. This overwhelming noise rendered analysis impossible, suggesting possible hardware issues with the reference channel or connections.

At this stage, we can only make informed guesses about the cause of the data quality issues observed. Given that the e-tattoo dataset from all participants displays a similar PSD profile, with a pronounced peak at 30 Hz and 60 Hz in nearly all channels, it suggests that the issue is not likely due to the recording procedures or device set up, but is likely due to hardware-related challenges. If human error during the recording process were causing data quality issues, we would expect to see variations in the PSD across different participants. For example, in the EEG recordings using StarStim, we observed 60 Hz noise in some participants but not in others. However, this noise was present in all channels and in almost every participant within the e-tattoo dataset. This leads us to believe that the recording procedure is less likely responsible for the noise issue. The consistent pickup of the 30 Hz noise across all channels indicates a probable issue with the ground channel in the hardware, such as a loose or damaged connection to the main digital signal processing (DSP) board, possibly resulting from shipping or handling.

Another possibility is that the e-tattoo device has an unstable reference channel. Typically, in EEG devices, the ground channel provides a stable baseline, and the reference channel offers a biopotential signal compared against this baseline. The StarStim, for example, has separate channels for ground (named as driven right leg [DRL]) and reference (named as common mode sense [CMS]). As highlighted by Belkhiria and Peysakhovich (2021), the CMS serves as a reference point to which EEG signals can be compared and measured against. The DRL plays a critical role in optimizing the quality of EEG recordings by minimizing electrical noise and drift. Proper contact between the DRL and CMS allows for substantial reduction of 60 Hz interference and improves the fidelity of the obtained readings. Maintaining an appropriate connection is vital for collecting clean, high-quality EEG data that accurately captures the electrical patterns generated by participants.

Although this may not be the ideal setup, it was a necessary compromise due to the device’s size constraints. If the reference channel is too close to the ground channel, it may result in extra noise being introduced into the EEG signal, complicating the accuracy of data interpretation. Furthermore, we noted that the e-tattoo device exhibited an inconsistent sampling rate, a fact also acknowledged by the e-tattoo device creators at UTA. The e-tattoo device has an ideal sampling rate at 250 Hz. During our experimental testing, the e-tattoo EEG sampling rate dropped to as low as 147 Hz in some cases. This variability in the sampling rate complicates data analysis, potentially necessitating data interpolation. However, if not handled correctly, interpolation can lead to inaccurate results for long recording sessions. The UTA group is aware of this issue and is currently working on a solution. Another issue we encountered with the e-tattoo device prototype was packet and data loss.

During experimental testing, we were unable to evaluate one participant’s e-tattoo EEG data due to some unknown issue with connectivity and data not transferring from the e-tattoo to the recording device. Despite not obtaining usable EEG data from the e-tattoo device, this does not detract from its potential advantages. The device's small, compact design allows it to be comfortably worn under a helmet, making it highly suitable for collecting EEG signals in a real-world environment. Additionally, the e-tattoo prototype has been previously shown to capture reliable, high-quality data. As the prototype is in early stages of development and progress is currently being made, there is high hope for future practical use of the device. From our experiences, we propose several recommendations for the project's future. First, the durability of the e-tattoo hardware should be significantly enhanced to withstand rough handling and shipping. This aspect is particularly crucial in a cockpit environment, where pilots cannot afford to handle such devices delicately. Second, a testing tool should be provided with the e-tattoo hardware, allowing researchers to check its functionality before deploying it with participants. Third, the recording software for the device should be upgraded to include a feature that alerts users to poor data quality. Fourth, an important update for the software would be the addition of a calibration session before beginning data collection to ensure data quality.

Conclusion

Overall, wearable forehead EEG/EOG sensor systems hold substantial promise for monitoring aviator cognitive state and enhancing aviator safety. The non-invasive, portable nature offers significant advantages over current laboratory-grade equipment. However, additional development and rigorous, mission-relevant testing protocols are still required before sensors like the e-tattoo prototype can be adopted for military use. With future refinements to enable robust performance in extreme environments, aviation-tailored design, and extensive validation in high-fidelity simulated and actual flight, sensor systems like this e-tattoo prototype may someday fill the pressing need for mental state monitoring in next-generation aircraft. Significant research investments remain to fully mature these emerging technologies for the unique and unforgiving aviation conditions. The immense potential benefits for pilot safety, aircraft capability, and mission effectiveness continue to compel progress toward making this goal an operational reality.

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Appendix A. Acronyms and Abbreviations

Ag/AgCl	Silver/Silver Chloride
BDI-II	Beck Depression Inventory-II
cm	Centimeter
CMS	Common Mode Sense
DB	Decibels
DRL	Driven Right Leg
EEG	Electroencephalography
EOG	Electrooculography
FPC	Flexible Printed Circuit Board
Hz	Hertz
KSS	Karolinska Sleepiness Scale
NASA TLX	National Aeronautics and Space Administration Task Load Index
PSD	Power Spectral Density
PVT	Psychomotor Vigilance Task
STAI	State-Trait Anxiety Inventory
USAARL	United States Army Aeromedical Research Laboratory

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