A Flight-helmet Compatible Closed-loop Electrooculography and Vagal Nerve Stimulation Device for Fatigue Mitigation in Pilots

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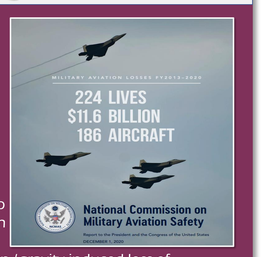
Abstract

To address the Air Force's needs to monitor the vitals and cognitive states of military craft and plane operators, QUASAR is developing an ecG eOg Electric Stimulator (GO E-Stim), a closed-loop fatigue detection and mitigation solution that could reduce the rate of mishaps and improve operational efficiency. QUASAR will embed its high-fidelity and artifact resistant electrooculography (EOG) sensors, along with temperature sensors and optical pulse oximetry (SpO2) sensors into a headband that can be worn with an avionics helmet. In addition, Soterix Medical Inc (SMI) will provide transdermal vagus nerve stimulator (tVNS) to interface into this headband. An EOG-based fatigue detection algorithm will be implemented to trigger the stimulation in a closed loop fashion. The system will be tested in flight simulations and on a plane.

Military Health Significance

The National Commission on Military Aviation Safety identified that the military's sustained high tempo is causing fatigue-related aviation accidents in all military branches, and that between 2013 and 2020, 224 lives, and 186 aircraft were lost due to military aviation mishaps amounting to losses of $11.6 billion. *



It is well documented that there is a negative impact on mission performance and an increased risk of accidents associated with sleep deprivation, extended time on intense attention demanding tasks, physical exertion, acute or chronic stress, strong and extended acceleration (gravity induced loss of consciousness (G-LOC)), as well as hypoxia, etc.

* National Commission on Military Aviation Safety, Military Aviation Losses 2013-2020. (2020) Accessed online 6/12/2022 https://s3.documentcloud.org/documents/20419375/ncmas_final_report.pdf

Background

The Air Force has identified electro-oculogram (EOG), thermal imaging, and heart rate variability (HRV) as promising approaches for cognitive workload monitoring and fatigue detection and neuromodulation as a promising approach for fatigue mitigation in aerospace environments.

Existing technologies often suffer from poor signal quality, reliability issues in high-motion environments, and challenges in integrating with aerospace equipment. QUASAR, a leader in physiological monitoring technologies, has experience integrating high-fidelity sensors into military-grade helmets for real-time operator state monitoring (OSM). QUASAR's patented hybrid capacitive and resistive dry electrode technology has been developed under DoD funding to address this usability challenge by enabling gel-free high-fidelity EXG recordings that are resistant to motion and electrical artifacts. This technology has been validated in various military relevant environments, including dismounted warfighters, and simulations such as UAV control and stationary flight simulators.

In this project, QUASAR will integrate dry electrode EOG and temperature sensors and commercial SpO2 sensors into a headband compatible with avionics helmets. QUASAR will incorporate a transcutaneous vagus nerve stimulation (tVNS) system from SMI to provide closed-loop fatigue mitigation.

Company Overview

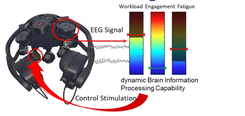
Quantum Applied Science and Research (QUASAR) has developed revolutionary noninvasive electrophysiological sensors with machine learning algorithms for cognitive & physiological monitoring in military, medical, & consumer applications.

QUASAR's Dry Sensor Interface (DSI) EEG technology is being commercialized by Wearable Sensing for novel applications in the fields of Brain-Computer Interface (BCI), Cognitive Monitoring, Augmented Cognition, Biomarkers, Neurofeedback, Neurorehabilitation, Neuroergonomics, Neuroeducation, etc.

QUASAR is experienced in integrating multimodal wearable physiological sensors into military helmets and armor for operator state monitoring.

Wearable, Low Power Ballistic Impact Detection System
USAMRAA SBIR Phase I/II contract: W81XWH-06-C-0045
POP: 2005 - 2009. PM: Steve Van Albert (WRAIR)

ECG + Ballistic Impact Detection Sensors (BIDS) integrated into body armor

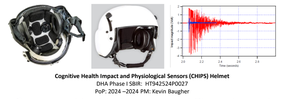


Closed-Loop Feedback Control for Transcranial Direct Current Stimulation
USAF/AFMC Phase I/II SBIR: FA8650-18-P-6920 / FA8650-19-C-6041
PoP: 2017 –2022 PM: Richard "Andy" McKinley

Closed-loop Improved Cognition (CLIC) headset

Dry Electrode Flight Integrated EEG System Helmet
DHA Phase I/II SBIR: W81XWH22P0130 / HT942523C0048
PoP: 2023 –2026 PM: LCDR Adam Preston USN-NAMRU DAYTON-OH

Dry Electrode Flight Integrated EEG System (DEFIES) Helmet



Cognitive Health Impact and Physiological Sensors (CHIPS) Helmet
DHA Phase I SBIR: HT942524P0027
PoP: 2024 –2024 PM: Kevin Baugher

Cognitive Health, Impact, and Physiological Sensor (CHIPS) Helmet with BIDS

Research Sponsorship & Disclosures

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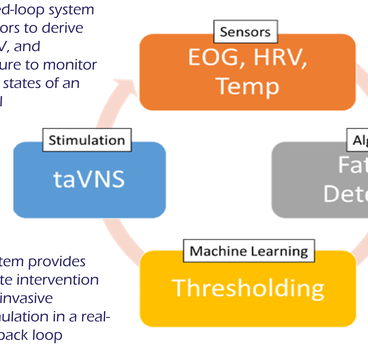
N. McDonald, K. Ermolaev, T. McManus, M. Steindorf, M Poquette, & W. Soussou are employees of QUASAR Inc. Y. Valter, G. Turnquist, K. Nazim, & A. Datta are employed by Soterix Medical, Inc., which manufactures and sells components of the developed device. Abhishek Datta holds equity in Soterix Medical.

Conceptual Framework

1. A closed-loop system uses sensors to derive EOG, HRV, and temperature to monitor cognitive states of an individual

2 . The system assesses and classifies levels of fatigue using a machine learning algorithm

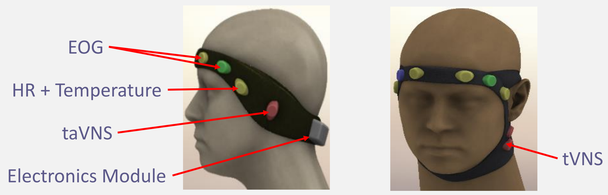


4. The system provides appropriate intervention via a non-invasive neurostimulation in a real-time feedback loop

3. The system monitors levels of fatigue and defines a personalized threshold for intervention

Electronics integration

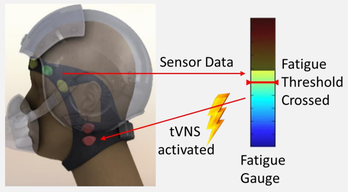
Concept rendering of headband positioning sensors



Concept rendering of a headband that seamlessly integrates the EOG, HR and temperature sensors and a transcranial auricular vagus nerve stimulation (taVNS) or a transcutaneous vagus nerve stimulation (tVNS) system

Closed-loop wearable system compatible with avionics helmet

- Multimodal sensor headband records physiological signals
- Individualized algorithm uses sensor data to objectively assess fatigue
- When fatigue threshold is crossed, the Vagus Nerve is electrically stimulated
- Vagus Nerve stimulation activates brainstem and increases alertness
- Pilot or operator performance improved over longer periods



Helmet-Compatible Headband Design

Design concepts for the GO E-Stim headband

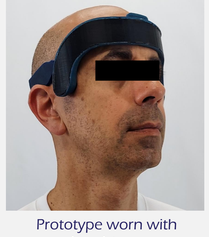
Prototype made of stretchable fabric.

Design drawing of inside of headband with labels showing electrode locations.

Headband assembly: Black = silicon rubber Red = outer, stiffer plastic

Integration into HGU-68/P Helmet

Latest prototype design made of silicon and plastic.



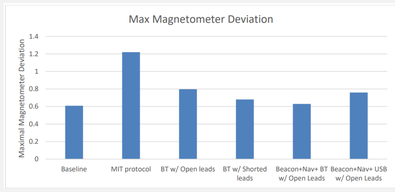
Prototype worn with headstrap.

Prototype worn under an HGU-68/P flight helmet.

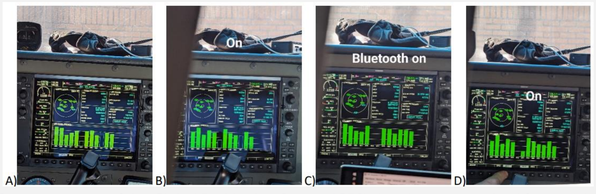
- Headband made from molded silicon rubber
- Flexible headband conforms to the shape of the wearer's forehead
- Sensors protrude on soft retracting silicon for controlled contact pressure
- Plastic tabs allow for easy coupling with a helmet

Ramp and Flight Testing Measurements

The GO E-Stim device did not interfere with the plane's electronic equipment during ramp testing



Maximal magnetometer deviations plotted for each experimental condition.



Screen captures of the Global Positioning System (GPS) signal power received from each detected satellite (one green bar per satellite) in various modes of operation of the GO-E-Stim Device: A) OFF, B) ON, C) streaming via BT, D) stimulation activated.

A flight was safely conducted with the GO-E-Stim actively acquiring and transmitting data, without any observed operational challenges

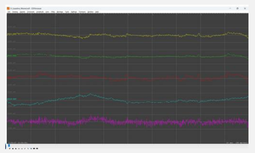
Individual wearing GO E-Stim device and flight communication headset on top of it

Individual wearing GO E-Stim device during flight

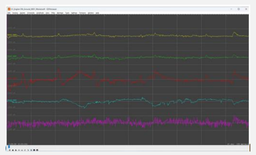
GPS signal checker detected over 13 satellites with sufficient power during flight with GO E-Stim

The internal system tester passed on all its parameters during flight with GO E-Stim

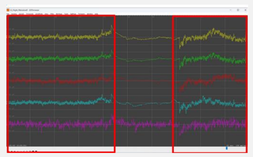
The plane's engine does not generate artifacts in the GO E-Stim data during ramp testing



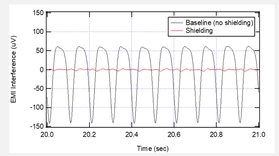
Baseline recordings with plane systems and engine OFF



Baseline recordings with plane systems and engine ON



High frequency artifacts generated by the pilot communicating to the control tower



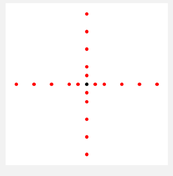
Bench-top tests indicate shielding of headset and main electronics reduces EMI pickup.

Results

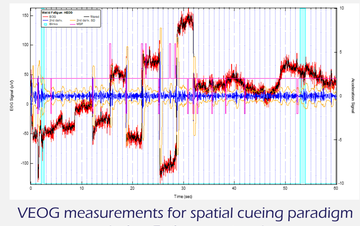
- The GO E-Stim device did not interfere with the plane's magnetometer, GPS or other electronic equipment.
- There were no observable artifacts in the GO E-Stim data due to the engine starting up or the device wearers touching the instruments and surfaces in the cockpit.
- High-frequency artifact appeared consistently whenever the pilot communicated with the tower control via the radio
- QUASAR has identified the circuit node most responsible for pickup of EMI interference via shielding tests and has suggested several shielding configurations to reduce EMI pickup to be used in the next prototype design.

Feasibility Study: Fatigue Detection Protocol

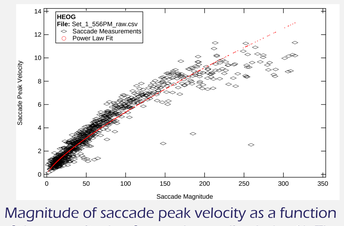
Simultaneously EOG and EEG data collection device used in preliminary tests.



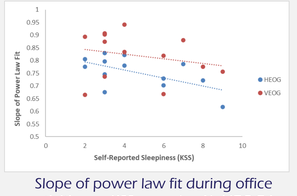
Array of fixation points for spatial cueing paradigm.



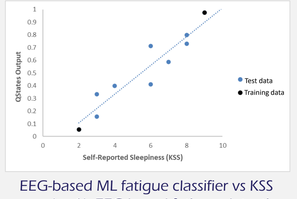
VEOG measurements for spatial cueing paradigm during Fatigue protocol.



Magnitude of saccade peak velocity as a function of the magnitude of saccade amplitude (n=1). The slope of a linear fit to log-transformed data can be interpreted as the exponent of the power law.



Slope of power law fit during office activities vs. KSS score (n=1). HEOG is correlated with KSS score (p=0.015).



EEG-based ML fatigue classifier vs KSS scores (n=1). EEG-based fatigue detection is strongly correlated with KSS (p=0.004).

Preliminary Results

- Saccade peak velocity-amplitude relationship consistent with Di Stasi et al. (2013).
- HEOG saccade peak velocity and magnitude during office task shows a strong correlation with KSS scores.
- EEG-based fatigue detection shows a very strong correlation with KSS scores.

Conclusions

- QUASAR integrated physiological sensors into an under-helmet headband and interfaced it with a tVNS system.
- The GO E-Stim electronics did not interfere with aircraft electronics during ramp testing and flight.
- The only interference to GO E-Stim was from communications to radio tower, which was mitigated with new shielding.
- QUASAR's EOG and fatigue detection models can accurately detect saccades and participant fatigue respectively.
- The GO E-Stim system is showing promise for use as a closed-loop fatigue mitigation solution for long flights.