Functional Near-Infrared Spectroscopy (fNIRS) in an Aerospace Environment: Challenges and Considerations

Joseph Geeseman; Stephanie Balters; Olivia Fox Cotton; Zachary Kiehl; Lisa Lucia; Caitlin Tenison

This column is coordinated and edited by Valerie E. Martindale, Ph.D. These articles are not peer-reviewed. The AsMA Science and Technology Committee provides the Watch as a forum to introduce and discuss a variety of topics involving all aspects of civil and military aerospace medicine. Please send your submissions and comments via email to: vemartindale@hotmail.com. Watch columns are available at www.asma.org through the "Read the Journal" link.

Flying an aircraft is a complex task that requires orchestrated contributions from distributed brain regions to accomplish the wide array of sensory, motor, and cognitive processes associated with successful aircraft operations. Visual processes include peripheral processing of optic flow from passing scenery upon takeoff and landing, foveal processing of stimuli including flight instruments and displays, navigation aids, and visual scanning for other aircraft. Employing nearly the whole body, motor processes include depressing foot pedals to change the aircraft's yaw, using the arms and hands when manipulating flight controls to adjust velocity, altitude, and lateral position of the aircraft, and flexing and extending trunk muscles and available appendages to keep physically stable through aircraft movement. The demanding communications tasks in a flight environment require synchronous motor, perception, and language processing regions of the brain. Finally, pilots utilize many other cognitive processes during successful flight including decision making, attention, planning, and complex problem solving. Not only do pilots use disparate regions of the brain to accomplish some of these tasks (e.g., perception, motor tasks), but many of these tasks also require distributed connectivity of multiple brain regions (e.g., communications, spatial planning). If these statements are true, what exact regions are highly utilized during aircraft operations, and how do these brain regions interact during the various phases of flight?

Researchers use a variety of physiological indicators and behavioral measures in the cockpit to identify and evaluate cognitive states like situational awareness and workload, or simply for making engineering design decisions.[3] Commonly used indicators include heart rate and heart rate variability, breathing rate, pupillometery, skin conductance, eye tracking, vocal analysis, response times and response errors, and other behavioral metrics. Although these metrics can be used to infer the underlying brain activity and associated cognitive states, none of them are direct measures of neural activity in the brain.

Neural activity presents itself as a particularly compelling data source that allows for objective, quantifiable measure of human cognition and correlated overt behavior. Being able to monitor and understand the brain easily, in real time, and across many contexts offers a profound opportunity to evaluate and influence individual warfighter (and possibly team) readiness. Valid and reliable neurotechnologies to assess individual warfighter and team states allow us to better understand brain function (e.g., how the brain responds to stress), monitor the brain (e.g., assess fatigue and engagement), protect the brain (e.g., identify practices that may help the brain resist or recover from stressful events), repair the brain (e.g., evaluate the impact of restorative activities such as nerve substitution transplantation or sleep), and enhance the brain (e.g., improve cognitive function via transcranial direct current stimulation [tDCS][4] or neurofeedback[6]).

Despite the broad applications of brain monitoring, a portable and ruggedized solution for in-the-field neural state monitoring of warfighters does not exist. Existing techniques for objectively evaluating physiological states (e.g., hypoxia, dehydration) and psychological states (e.g., attentiveness, alertness), such as fMRI and EEG, are not well suited to operational environments. They require large rooms ($\sim$20 $\times$ 30 feet) for stationary equipment or are negatively impacted by movement

From the Naval Air Warfare Center Aircraft Division, United States Navy, NAS Patuxent River, MD; Center for Interdisciplinary Brain Sciences Research, Stanford University, Palo Alto, CA; Aptima, Inc., Woburn, MA; and Soar Technologies, Ann Arbor, MI.

DOI: https://doi.org/10.3357/AMHP.5723.2020

artifacts and ambient electrical noise. The maturing technology of functional near-infrared spectroscopy (fNIRS) offers some advancements over fMRI and EEG and may be better suited for in-the-field neural state monitoring. fNIRS more capably provides brain region specificity (similar to the spatial resolution of fMRI) as well as a sufficient sampling rate (better temporal resolution than fMRI, though not as good as EEG) while also being highly portable, less obtrusive, and noninvasive. Despite the advantages of fNIRS over other neurotechnologies, however, most commercial fNIRS devices remain bulky, expensive, and generally difficult to deploy in an operational environment. We posit that recent advances in fNIRS make it a leading contender for use in the cockpit to collect brain activity data in flight.

fNIRS can provide a portable means of collecting information about brain function. fNIRS uses optical spectroscopy to measure blood oxygenation and flow in cortical tissue. According to the theory of neurovascular coupling, when neural activity consumes oxygen, this depletion leads to changes in local cerebral hemodynamics to increase blood flow to these regions. These changes produce signals that can be decomposed into various spatial, spectral, and temporal fNIRS features. With this information, it is possible to measure not only brain activity but also decode information about a person's physiological condition. Prior research using fNIRS has focused primarily on detection of a single state such as workload, attention, stress, or blood oxygenation level (See **Table I**). We propose that the future of operational fNIRS will synthesize these different uses of fNIRS signals and result in an fNIRS system for the detection of multiple complex physio-cognitive states.

Using online and offline analysis approaches, fNIRS detects the cognitive state of individuals in both laboratory and real-world settings (Table I). Typically, these studies focus on a specific, easily manipulated state. In many of these studies, an initial experimental manipulation is used to record fNIRS data from conditions where individuals are and are not in that state. Next, a machine learning classifier, such as a support vector machine (SVM) or linear discriminate analysis (LDA), is trained to detect patterns in the data indicative of that state. This classifier is then applied to an unlabeled set of data to predict what cognitive state generated that data. Data-processing, hyper parameter tuning, and classifier selection can vary between the fNIRS system used, task type, and experimental conditions; however, the steps supporting state estimation are largely the same.

Some cognitive state studies and how they may impact aerospace performance are detailed below:

- **Attention:** fNIRS is frequently used to study attention in many contexts, including attention allocation, selective attention and sustained attention. Examination of various aspects of attention could be informative regarding mission readiness.
- **Cognitive Workload:** Investigations of cognitive workload have been conducted using fNIRS in the aviation domain, comparing prefrontal activity of pilots during various tasks, but not in an actual cockpit.
- **Stress:** Stress is a psychophysiological construct quantified via differences in hemodynamic response of the prefrontal cortex. Relative levels of stress, as well as different types of stress (i.e., mental compared to physical) could impact mission readiness.
- **Fatigue:** Recent research assessing fatigue during prolonged image interpretation tasks is particularly relevant for sensor operators given the nature of their tasking. Other relevant fNIRS work is aimed at detecting and predicting drowsiness.
- **Motor Learning:** fNIRS technology has been used to study hemodynamic changes during motor tasks. Efforts to understand the underlying motor signals accompanying the learning of a complex motor task could impact training especially when assessing novices and experts.
- **Task Engagement:** Researchers have also assessed pilots' engagement with a flight task via combined EEG/fNIRS studies, with fNIRS analysis focusing on wavelet coherence.
- **Physiological Signals:** fNIRS technologies also have the ability to detect physiological changes such as dehydration and caffeine consumption, both of which contribute to mission readiness.

It should be noted that fNIRS does not directly measure the cortical activity of an individual. Rather, optical imaging supports detection of the blood-oxygen-level dependent (BOLD) response indirectly through identifying changes in oxyhemoglobin (HbO) and deoxyhemoglobin (HbR). Interestingly, from measuring these low-level processes, an experimenter can derive additional measures like heart rate, respiration, and other measurements that may be of interest to aerospace researchers. **Table II** lists some physiological and cognitive information that can be extracted from recording HbO/HbR.

Table I. Single Cognitive and Physiological State Studies Completed with fNIRS.*

COGNITIVE STATE DETECTED	PRIOR RESEARCH DEMONSTRATING DETECTION CAPABILITIES WITH fNIRS
Workload	Peck et al., 2014; Fishburn et al., 2014; Gabbard et al., 2017; Causse et al., 2017; Causse, Chua, & Remy, 2019; Gateau et al., 2015
Anxiety/Stress	Al-Shargie et al., 2016; Al-Shargie, 2019; Fakhr, Jeon, & Bose, 2015
Attention/Mind-wandering	Durantin, Dehais, & Delorme, 2015; Harrivel et al., 2013; Hincks et al., 2017; Verdiere, Roy, & Dehais, 2018; McKendrick, 2019; Eskicioglu et al., 2019; Carter, Russell, & Helton, 2013
Affect	Oonishi et al., 2014; Savran et al., 2006; Fakhr, Jeon, & Bose, 2015
Cognitive processing	Solovey et al., 2011; Bhutta et al., 2015
Fatigue	Nihashi et al., 2019; Khan, Naseer, & Khan, 2019; DeHais et al., 2018
Motor Learning	Ono et al., 2015; Heinze et al., 2019
Physiological Signals	Giles et al., 2019; Heilbronner, Hinrichs, Heinze, & Zaehle, 2015

* Citations noted as examples within the text are excluded in this reference list for space considerations.

Table II. Physiological Measures That Can be Extracted from NIRS Sensing.[2]

SYSTEM	MEASURE	INDICATION
Cardiopulmonary	Heart rate, heart rate variability	Hypoxia, dehydration, stress, anxiety
Hemodynamic Response	Cerebral blood flow velocity, blood oxygenation	Workload, attention, hypoxia, dehydration
Respiration	Respiratory rate	Hypoxia, anxiety
Brain Activity	Spatial and temporal information about brain activation	Arousal, workload, attention, hypoxia, dehydration

Not only must this potential operational fNIRS system address the cognitive and physiological multistate assessment previously mentioned, but an operational fNIRS system must also solve problems with sensor placement, movement artifacts, and environmental impacts to data quality (e.g., sunlight). Although there are many signal processing and analysis approaches that can be used to clean data signals, there is no substitute for clean data, and such methods often require significant computational resources for online operation. The form factor of the hardware has a significant impact on the signal quality and is generally the biggest challenge preventing the use of fNIRS in operational environments[5]. The primary sources of noise impacting the collection of fNIRS signals are: 1) motion of the light source and optodes, which causes disruption or fluctuation in the signal detected; and 2) individual differences in skin tone, hair color, and head shape, which cause variations in the quality of signal. These challenges can be addressed in the form factor of the design, placement of sensors, noise attenuation strategies, and, when necessary, machine learning or auto-preprocessing of data.

As indicated by Adamovsky et al.,[1] there is a need for an operational fNIRS system that satisfies the constraints typically faced in applied settings. Fortunately, the Defense Health Agency recently awarded a new Small Business Technology Transfer grant (DHA STTR 19B-001) to support the development of such a system. Performers on this project will explore the viability of an operational aerospace fNIRS system by evaluating form fit, sensors, data cleaning and processing, and multistate detection as outlined in this article. Furthermore, advanced techniques like hyperscanning and neurofeedback will be considered for their applicability in an aerospace environment for activities involving training, crew planning, flight performance, and many other potential areas of interest that are yet to be determined.

REFERENCES

1. Adamovsky G, Mackey JR, Harrivel A, Hearn TA, Floyd BM. Toward adaptation of fNIRS instrumentation to airborne environments. In: AIAA Infotech@Aerospace (I@A) Conference. August 19–22, 2013; Boston, MA. AIAA 2013-4895.
2. Adan A. Cognitive performance and dehydration. J Am Coll Nutr. 2012; 31(2):71–88.
3. Geeseman J, Patrey J, Davy C, Perditto K, Zernickow C. The impact of conflicting spatial representations in airborne unmanned aerial system sensor control. Patuxent River, MD: NAVAIR Patuxent River; 2016. Available from: https://apps.dtic.mil/sti/citations/AD1009801.
4. Jin H, Hou LJ, Wang ZG. Military brain science–how to influence future wars. Chin J Traumatol. 2018; 21(5):277–280.
5. Kassab A, Le Lan J, Vannasing P, Sawan M. Functional near-infrared spectroscopy caps for brain activity monitoring: a review. Appl Opt. 2015; 54(3):576–586.
6. Sulzer J, Haller S, Scharnowski F, Weiskopf N, Birbaumer N, et al. Real-time fMRI neurofeedback: progress and challenges. Neuroimage. 2013; 76:386–399.

STATEMENT OF OWNERSHIP, MANAGEMENT AND CIRCULATION

(Required by 39 U.S.C. 3685)

1. Title of Publication: *Aerospace Medicine and Human Performance.* 2. Publication No. 008-760. 3. Date of Filing: October 1, 2020. 4. Frequency of Issue: Monthly. 5. No. of Issues Published Annually: 12. 6. Annual Subscription Price: $270. 7. Complete Mailing Address of Known Office of Publication: Aerospace Medical Association, 320 S. Henry St., Alexandria, VA 22314-3579. 8. Complete Mailing Address of Headquarters or General Business Office: Aerospace Medical Association, 320 S. Henry St., Alexandria, VA 22314-3579. 9. Full Names and Complete Mailing Address of Publisher, Editor, and Managing Editor: Pubisher -- Aerospace Medical Association, 320 S. Henry St., Alexandria, VA 22314-3579. Editor -- Frederick Bonato, Ph.D., 2641 John F. Kennedy Blvd., Jersey City, New Jersey 07306-5943. Managing Editor -- Pamela C. Day, B.A., Aerospace Medical Association, 320 S. Henry St., Alexandria, VA 22314-3579. 10. Owner: Aerospace Medical Association, 320 S. Henry St., Alexandria, VA 22314-3579. 11. Known Bondholders, Mortgages, and other Security Holders Owning or Holding 1 Percent or More of Total Amount of Bonds, Mortgages, and Other Securities: None. 12. For Completion by Nonprofit Organizations Authorized to Mail at Special Rates: The purpose, function, and nonprofit status of this organization and the exempt status for Federal income tax purposes has not changed during the preceding 12 months.
13. Publication Name: *Aerospace Medicine and Human Performance.*
14. Issue Date for Circulation Data: September 2020.

15. Extent and Nature of Circulation:	Ave. No. of Copies Each Issue During Preceding 12 Months	No. Copies of Single Issue Published Nearest Filing Date
a. Total no. copies	2002	1802
b. Paid circulation		
1. Paid/requested outside county mail subscriptions	1051	989
2. Paid in-county subscriptions	0	0
3. Sales through dealers and carriers, street vendors, and counter sales	612	514
4. Other classes mailed through USPS	0	0
c. Total paid/requested circulation	1664	1503
d. Free distribution:		
1. Outside county	0	0
2. In-county	0	0
3. Other classes mailed through USPS	0	0
4. Free distribution outs	30	30
f. Total free distribution	30	30
g. Total distribution	1694	1533
h. Copies not distributed	308	269
i. TOTAL	2002	1802
Percent Paid and/or Requested Circulation	98.22%	98.04%