Article published in the journal Aviation Space and Environmental Medicine (ASEM), Vol. 76, 7, Section II Supplement, July 2005

Monitoring and Predicting Cognitive State and Performance via Physiological Correlates of Neuronal Signals

Michael B. Russo[1], Melba C. Stetz[2], and Maria L. Thomas[3,4]

[1]U.S. Army Aeromedical Research Laboratory, Ft. Rucker, AL
[2]HQ, U.S. Army Medical Research and Materiel Command, Fort Detrick, MD
[3]USAARL-North / Navigator Development Group, Inc., Enterprise, AL
[4]Johns Hopkins University School of Medicine, Baltimore, MD

Corresponding Author:
COL Michael Russo, M.D.
U.S. Army Aeromedical Research Laboratory
6901 Farrell Drive
Fort Rucker, AL 36362
michael.russo@us.army.mil

Abstract

Judgment, decision-making, and situational awareness are higher-order mental abilities critically important to operational cognitive performance. Higher-order mental abilities rely on intact functioning of multiple brain regions, including prefrontal, thalamus, and parietal areas. Real-time monitoring of individuals for cognitive performance capacity via an approach based on sampling multiple neurophysiologic signals and integrating those signals with performance prediction models, potentially provides a method of supporting Warfighters' and commanders' decision-making and other operationally-relevant mental processes and is consistent with the goals of augmented cognition. Cognitive neurophysiological assessments that directly measure brain function and subsequent cognition include PET, fMRI, mass spectroscopy, near infrared spectroscopy, MEG, and EEG; however, most direct measures are not practical to use in operational environments. More practical, albeit indirect measures that are generated by, but removed from the actual neural sources, are movement activity, oculometrics, heart rate, and voice stress signals. The goal of papers in this section is to describe advances in selected direct and indirect cognitive neurophysiologic monitoring techniques, as applied for the ultimate purpose of preventing operational performance failures. The manuscripts present data acquired in a wide variety of environments, including laboratory, simulator, and clinical arenas. The manuscripts discuss cognitive neurophysiologic measures such as digitial signal processing wrist-mounted actigraphy; oculometrics such as blinks, saccadic eye movements, pupillary movements, the pupil light reflex; and high frequency EEG. These neurophysiological indices are related to cognitive performance as measured through standard test batteries and simulators with conditions including sleep loss, time on task, and aviation flight-induced fatigue.

Active cognition during complex and sustained operations is a critical component for success in current and future military operations. Visual-auditory perception, as maintained by the parietotemporal lobules, must absorb the depth and breadth of the battlefield and forward the complex mental constructs to the thalamus. Integrative perceptual processing, as occurs in the thalamus, must sift the myriad of inflowing facts, generate an elemental thought, and project the nascent construct to multiple cortical regions, including the prefrontal cortex. In the prefrontal cortex, the incipient thought may be brought to attention and either maintained in working memory, sent for longer-term memory storage, or deemed irrelevant and forgotten. The prefrontal cortex is the brain region primarily responsible for selecting thoughts relevant to the changing operational environment and for deciding which to integrate into performance. The prefrontal cortex holds and prioritizes significant details while releasing useless facts. Attention is the process by which the prefrontal regions scan thoughts and maintain them in consciousness.

Judgment and decision-making are crucial operational functions that ideally utilize higher-order cognitive pathways to weigh the cost versus the benefits of a particular action. When higher-order pathways and prefrontal control are applied, risk-taking and decision-making may objectively occur. If the higher-order controls are removed, as can happen during periods of stress and sleep deprivation, judgment and decision-related behaviors may disassociate from the higher-order pathways and instead generate from visceral feelings through the limbic system. Fear and anger, also limbic-system-generated and present on the battlefield, must be controlled lest they overwhelm prefrontal cognitive processes. Successful battlefield control utilizes extrovision, meaning the motivation and mental agility to mine the databanks of the digital battlefield for critical information, over introvision, or the desire to perseverate upon a failing or ineffective internally generated strategy. Mental agility refers to the ability to rapidly shift from one informational datastream to another, and effectively integrate the relevant components of each into cogent thoughts.

A tool like the Military Decision Making Process (MDMP; 2), which typically utilizes a several step decision aid process (e.g., mission analysis, course of action development, analysis, comparison, and approval) has been developed to apply thoroughness, clarity, sound judgment, logic, and professional knowledge to the decision-making process. MDMP provides a framework for facilitating use of higher order cognitive processes, so that planners can assist the Warfighter*, the commander, and the staff in thoroughly examining a battlefield situation and in reaching sound decisions based on logical estimates.

On the battlefield, situational awareness, a crucial operational function involving multiple attention and memory circuits, reflects the degree of accuracy to which one's perception of the current environment mirrors reality. In order to achieve situational awareness dominance, Warfighters must stay focused and alert in a three dimensional battlespace. The present battlefield is more challenging and demanding than in the past, with more complex C4ISR (command, control, communications, intelligence, surveillance and reconnaissance) information and processes (5).

Under emerging network-centric warfighting doctrine, C4ISR means are being distributed to all operational levels, beginning with the individual soldier. Seamless communications facilitate transfer of potentially overwhelming amounts of information to any combat platform (i.e., tank or aircraft) and to all command levels. Consequently, with the increase in sophistication and reliance upon technology, Warfighters must anticipate battlefield operations and recognize critical datum in order to decide and act more quickly and effectively than the enemy.

Real-time monitoring of individuals for cognitive performance capacity via an approach based on sampling multiple neurophysiologic signals and integrating those signals with performance prediction models, potentially provides a method of supporting Warfighters' and commanders' decision-making and other operationally-relevant mental processes. Identifying and validating measures of cognitive performance, integrating them into models predicting operational performance, and optimizing the flow of information for decision-making supports the goals of the Defense Advanced Research Projects Agency (Information Technology Office) Augmented Cognition program. Augmented Cognition seeks to transform the human-machine interaction by making information systems sensitive to the individual Warfighter's capabilities and limitations. The Augmented Cognition program seeks to utilize neurophysiologic measures in concert with workload reduction algorithms as part of an effort to improve information processing ability by an order of magnitude. Integrating varied physiological measures, prioritizing signal transmissions and information content for immediate consideration of intervention, and developing suitable algorithms to automatically execute workload reduction systems continue to be non-trivial issues under considerable investigation. The goal of the papers in this section is to describe advances in the understanding of neurophysiology as they pertain to the monitoring of cognitive processing for the ultimate purpose of preventing operational performance failure. New in these papers are the relationships of specific neurophysiologic indices to elements of cognition and performance.

Cognitive neurophysiology is the study of changes in brain function (i.e., neural signals or brain activity) and the relationship of such changes to perceptual and thought generation processes. Basic research studies in human cognitive neurophysiology currently include the use of brain imaging techniques such as positron emission tomography (PET), functional magnetic resonance imaging (fMRI), mass spectroscopy, near-infrared spectroscopy (NIRS), magnetoencephalography (MEG), and electroencephalography (EEG) to measure brain activity changes at specific cortical (by surface electrodes) and subcortical sites (by implanted electrodes) during perceptual and cognitive task performance. A U.S. Army Medical Research and Materiel Command-sponsored PET study of complex cognitive task performance has shown that during sleep deprivation there is decreased brain activity in several regions mediating higher cognitive functions and alertness; these include the prefrontal and posterior parietal cortices and the thalamus (12, 13). Brain activity in specific subregions of the prefrontal cortex, the thalamus, and an area of the visual (occipital) cortex, were found to decrease across the 72-hour sleep deprivation period. These brain activity decreases correlated with the decreases in both cognitive performance and saccadic velocity (13). Of particular relevance to the issue of identifying indices for cognitive monitoring is that not only did the ocular measure (slowing saccadic velocity) correlate with the same pattern of brain activity as did the impairment in cognitive task performance, but it also directly correlated with the cognitive performance decrement ($r = 0.98$, $p < 0.01$). This finding supports the premise that the physiologic signals generated by, but removed from the actual neural sources, may be viable monitors of both cognitive performance and the integrity of intrinsic neural processing.

The utilization of advanced neurophysiologic techniques to monitor the signals generated by integrative neural processes (e.g., EEG), and/or their resultant physiologic outcomes (e.g., movement activity, heart rate indices, ocular responses, vocal expression) as indicators of brain function and behavior, is a major goal of applied cognitive neurophysiology. As suggested by the results of the PET-sleep deprivation study (12, 13), individual neurophysiologic measures could reflect specific aspects of neural processing, and integration of multiple measures could allow understanding of complex higher order processes.

In situations where cognitive neurophysiologic monitoring would be utilized, an assumption is that the tasks are critical enough to require application of all cognitive processes. Neurophysiologic techniques permit an unobtrusive, transparent (non-interactive) data gathering process that allows monitored individuals to focus all available cognitive reserves on the required performance task. A cardinal feature of many of the second-order cognitive neurophysiologic techniques is that they measure normally involuntary responses, such as EEG, pupil size, or heart rate. Measurement of involuntary responses allows individuals to focus completely on critical tasks, and removes the potential bias of motivational factors. In the direct cognitive performance assessment approach, an individual has to apply both time and motivation to the cognitive test. The degree to which monitoring techniques take into account the individual Warfighter's cognitive status (individual vs. group readiness/impairment) and the strength of the relationship between the neurophysiologic measures and operational performance outcomes are other essential characteristics of a cognitive neurophysiology based monitoring system.

In military operations, the potential usefulness of the cognitive neurophysiology approach would be to assess the Warfighters' cognitive readiness and to predict cognitive performance. The result of such an approach may be to reduce the occurrence of catastrophic failures and battlefield injury (military operational medicine), as well as to assess the extent of cognitive responsiveness should injury be unpreventable (combat casualty care). In the military operational medicine application, the ability of monitoring techniques to predict overall cognitive readiness before an actual operation can provide useful logistical information regarding fitness for duty, and can provide guidance as to whether fatigue countermeasures should be utilized (such as taking a sleep nap or using a pharmacologic strategy). A second military operational medicine application would provide the ability to predict cognitive performance decrements prior to a catastrophic failure. If imminent failure can be identified, then it potentially can be averted by warning the individual or members of the operational unit. If cognitive decline occurs or workload increases within a mobile platform, such as in an F-16 or Stryker vehicle, automated workload reduction could engage to more closely align cognitive reserves with essential tasks. In the combat casualty care application, neurophysiologic monitoring techniques could provide an indication of both cognitive responsiveness and life signs, potentially providing assistance in triage, aerial medical evacuation (MEDEVAC), and retrieval operations.

Ultimately, the complexity of combat operations, the numerous possible causes of cognitive performance impairment in the operational environment, and individual differences in response to various combat stressors may make it highly unlikely that a single neurophysiologic measure (direct or indirect) will be sufficient to serve as both an indicator of cognitive readiness assessment and a predictor of cognitive performance. Rather, a *system* or combination of unobtrusive monitoring techniques that include both the cognitive neurophysiology approach and the cognitive performance assessment approach may be warranted to obtain success.

An ideal neurophysiologic monitoring system applicable for individual use by the Warfighters would - by operational necessity - have to meet rigorous hardware and software specifications. For mobile vehicular platforms, which already have power and mounting capabilities, the specifications would be achievable at an earlier stage. In addition to identifying characteristics of a monitor's ability to assess an individual's general cognitive state, predict specific cognitive performance impairment, and be highly correlated with some aspect of operational performance, the recent Medical Research and Materiel Command workshop

(Cognitive Performance: The Future Force Warrior in a Network-centric Environment, St Pete Beach, Florida, 10-12 August 2004) also acknowledged the following as important criteria for development of an ideal neurophysiologic monitor: (1) No added weight; (2) No added power requirement; (3) Affordable and Cost-effective; (4) Unobtrusive and non-invasive; (5) Existence of device undetectable; (6) Transparent in that the monitored individual does nothing to initiate / sustain measurement; (7) Resistant to environmental and physiological artifact, or amenable to real-time artifact removal; (8) Relevant feedback provided to monitored individual through workload control feedback or automation; and (9) Information secure from unauthorized individuals. Proceedings of this meeting may be found at http://momrp-test.anteon.com/cognitive/.

Several neurophysiologic measures already meet some of the requirements outlined above, and their development and validation as fatigue assessment and prevention technologies, for example, are underway (3). Wrist-mounted actigraphy, oculometrics, electroencephalography, and voice stress characteristics meet enough of the required specifications to have attracted substantial research efforts. Validation studies showing the relationship of several of these measures to some aspect of performance are topics of scientific papers presented in this supplement. Two of these measures previously have been shown to be sensitive to the workload variations presented in the Warship Commander Task, designed as an analog to a Naval air warfare exercise (11).

DEPARTMENT OF DEFENSE DISCLAIMER

Citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services of these organizations. The views expressed in this paper are those of the authors and do not reflect the official policy or position of the Department of the Army, Department of Defense, or the U.S. Government.

REFERENCES

1. Fukuda K, Stern JA, Brown TB, Russo MB. Cognition, blinks, eye-movements and pupillary movements during performance of a running memory task. Aviat Space Environ Med. (In press.)
2. Headquarters, Department of the Army. Military decision making process (MDMP). In: Staff, organizations, and operations. Field Manual 101-5; 1997 May 31; Washington, D.C.: Department of the Army; 1997:5-1-31. See also http://www.dtic.mil/doctrine/jel/service_pubs/101_5.pdf retrieved March 18, 2005 from the World Wide Web.
3. Kloss JD, Szuba MP, Dinges DF. Sleep loss and sleepiness: physiological and neurobehavioral effects. Chapter 130. In: Davis L, Charney D, Coyl JT, Nemeroff C, eds. Neuropsychopharmacology: the fifth generation of progress. Philadelphia: Lippincott Williams & Wilkins; 2002:1896-1905. Retrieved March 10, 2005 from the World Wide Web: http://www.acnp.org/content-39.html.
4. LeDuc PA, Greig JL, Dumond SL. Involuntary eye responses as measures of fatigue in U.S. Army Apache aviators. Aviat Space Environ Med. (In press.)
5. Perry WJ. Command, control, communications, computers, and intelligence. In: Annual report to the President and the Congress. Part VI: Defense Components, 1995 Feb. Retrieved March 18, 2004 from the World Wide Web: http://www.defenselink.mil/execsec/adr95/c4i_5.html.
6. Rowland LM, Thomas ML, Thorne DR, et al. Oculomotor changes during partial and total sleep deprivation. Aviat Space Environ Med. (In press.)
7. Russo MB, Kendall A, Johnson D, et al. Visual perception, psychomotor performance, and complex motor performance during an overnight air refueling simulated flight. Aviat Space Environ Med. (In press.)
8. Russo M, Thomas M, Thorne D, et al. Oculomotor impairment during chronic partial sleep deprivation. Clin Neurophys 2003; 114:723-36.
9. Russo MB, Vo A, LaButta R, et al. Human biovibrations: assessment of human life signs, motor activity, and cognitive performance using wrist-mounted actigraphy. Aviat Space Environ Med. (In press.)

10. Sing HC, Kautz MA, Thorne DR, et al. High frequency EEG as measure of cognitive function capacity: a preliminary report. Aviat Space Environ Med. (In press).
11. St. John M, Kobus D, Morrison J. DARPA augmented cognition technical integration experiment (TIE). San Diego, CA: Space and Naval Warfare System Center; 2003 Dec. Technical Report No: 1905. See also: http://www.pacific-science.com/AppliedCognition/Augcog.shtml retrieved on the World Wide Web March 10, 2005.
12. Thomas ML, Sing HC, Belenky G, et al. Neural basis of alertness and cognitive performance impairments during sleepiness. I. Effects of 24 hours of sleep deprivation on waking human regional brain activity. J Sleep Res 2000; 9:335-52.
13. Thomas ML, Sing HC, Belenky G, et al. Neural basis of alertness and cognitive performance impairments during sleepiness. II. Effects of 48-72 hours of sleep deprivation on waking human regional brain activity. Thalamus Relat Syst 2003; 2:199-229.