Operational Neuroscience: Neurophysiological Measures in Applied Environments

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There is, without question, an interest within the military services to understand, account for, and adapt to the cognitive state of the individual warfighter. As the field of neuroscience has matured through investments from numerous government agencies, we are on the cusp of being able to move confidently from the lab into the field—and deepen our understanding of the cognitive issues embedded in the warfighting environment. However, as we edge closer to this integration—it is critical for researchers in this arena to understand the landscape they are entering—reflected not only in the challenges of each task or operational environment but also in the individual differences intrinsic to each warfighter. The research papers in this section cover this spectrum, including individual differences and their prediction of adaptability to high-stress environments, the influence of sleep-deprivation on neurophysiological measures of stimulus categorization, neurophysiological measures of stress in the training environment and, finally, real-time neural measures of task engagement, mental workload and vigilance. It is clear from this research, and other work detailed in this supplement, that the judicious use of neuroscience, cognitive psychology, and physiology in the applied environment is desirable for both researchers and operators. In fact, we suggest that these investigations merit a field designation unto their own: Operational Neuroscience. It is our hope that the discussion of this new field of study will galvanize others to increase the confidence and utility of this research through their own investigations.

Keywords: cognitive state, operational neuroscience, individual differences, training, neuroergonomics, operator functional state.

NEUROSCIENCE CAN BE broadly defined as the study of the nervous system, including both central and peripheral structures (13). One of the most compelling questions within this field is how the complexity of human behavior emerges from activities at the synaptic and cellular level (9). The driving force in neuroscience is the ultimate goal of understanding this progression from molecules to behavior. The majority of the work in this area is occurring at the molecular level, attempting to unravel the gene/cell/brain/behavior conundrum. This focus has been driven, in part, by substantial government investments recognized as the "Decade of Brain" (22). This sponsored research, which continued throughout the 1990s, enabled the creation of numerous laboratories, departments, and centers to directly investigate these questions (22). As a result of these ventures, and the enduring interest in the brain and cognition, neuroscience is in the midst of a revolution, with new insights on structure, function, and integration within the human brain occurring daily. Understanding the development and operation of the brain at its most basic level is essential to ameliorating the impact of a wide variety of diseases and disorders on the human condition. These investigations will, in turn, have a direct impact on the military, allowing the opportunity to repair and restore that which has been damaged by injury and war. Fundamental investigations will also enable artificial intelligence and cognitive computational systems to leverage how the brain actually functions for inspiration, mimicry, and modeling.

Operational Neuroscience

In spite of the continuing advancements in neurotechnologies, the current and dominant emphasis within the field fails to fully capitalize on the potential of neuroscience to address questions and applications outside of the clinical sphere. Novel wearable sensors and recording technologies, advanced signal processing, and real-time data acquisition and analysis are now available for use in applied environments (1,8,10,12,18). The expansion of neuroscience out of the purely clinical setting and into the operational realm will be of enormous benefit to both the military and the commercial/industrial community and should be encouraged and supported.

The utility of neuroscience in the applied realm merits a serious and continuing discussion. We maintain that the cumulative and escalating research in this domain signals the emergence of a new field of study: Operational Neuroscience. Although the designation "Operational Neuroscience" is novel, this field certainly encompasses the seminal and continued investments by the Department of Defense and the individual military services to investigate the cognitive state of the operator

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in real or simulated task environments (19,24). Operational Neuroscience, as a field, is about expanding the horizons of research on operator functional state into all of the potential areas that could benefit from what has already been demonstrated in the applied setting (Schmorrow D, Kruse A, Reeves L, Bolton A. Unpublished article; 2007).

There are multiple avenues to consider within this field, but we suggest that the majority of the effort should be directed to three focal points, the use of neuroscience in the design of systems, the training of individuals, and the monitoring of individual cognitive state in the operational setting.

The use of neuroscience and its potential impact on human factors, ergonomics, and interface design cannot be overstated. Due to recent advancements in real-time measures of cognitive activity through electroencephalography (EEG) in the workplace setting, it is now possible to assess an individual user's level of engagement, attention and workload while engaged with a particular interface (1,2). Data collection (EEG, eye tracking) can be time-stamped to the task or interface processes, so that moment-to-moment fluctuations in cognitive state can be correlated directly to overt behavioral interactions. These data can be collected without disturbing the user and can eliminate the need to infer workload solely from post-hoc measures or unnatural interruptions. In fact, Parasuraman recognized the potential of this approach in his innovative and forward-looking works on neuroergonomics (16,17). This area is ripe for exploitation in the design of military systems and has enormous dual-use implications within the industrial design and computer science communities.

The use of real-time neuroscience measures in the training environment is also a significant opportunity. Recent publications (5,7,14) demonstrating changes in brain dynamics during motor task learning highlight the burgeoning potential for the use of these signatures in real-time, interactive training systems. The neuroscience literature is becoming populated with research reports detailing the use of quantitative neuroimaging measures to differentiate between novice and expert subjects on complex tasks (4,11,20). Further explorations into this area of research may enable individualized training experiences based on the user's neurocognitive learning style, current status, and state of readiness for training. From fairly simple measures of levels of engagement or attention while learning a task to tracking the progress of skill acquisition via non-invasive imaging, the impact of neuroscience on training will be substantial.

Neurophysiological measures in actual operational settings are challenging, but not impossible. Recent efforts in the use of physiological and EEG measures in the field (mobile military subjects), have demonstrated the successful classification of operator state in real-time (8). Although this is perhaps the most daunting use of neuroscience technologies, investments in this arena have motivated the field of sensor mobility and real-time classification in ways that a clinical approach would not have produced. Considerable work in this area is described elsewhere in this supplement, and is not discussed in detail here.

Finally, although not specific to the operational neuroscience realm, the influence of the individual's non-task-related state must be factored into any applied setting. As we are uncovering through neurophysiology and neuroimaging, there are significant differences in the brains of individual subjects that must be accounted for in any deployable or operational system. Incorporating this information typically involves acquiring a subject's baseline neurophysiological state and tailoring a classification algorithm to that individual's specific brain dynamics (8,18; and Schmorrow D, Kruse A, Reeves L, Bolton A; unpublished article; 2007). In certain circumstances, baseline data is difficult, if not impossible to collect and solutions are needed for this issue. What also must be considered, and is markedly more difficult to collect, is the task-*independent* cognitive state of the user. This may involve the impact of ongoing conditions related to stress, extreme environments, sleep deprivation, and other physiological conditions that intersect with cognition (3,15,23). Ongoing work is focused on rapid assessment of these states with an eye towards prediction of their impact on task completion in the operational environment (6,25). With a baseline of the individual, from these multiple perspectives, the utility of operational neuroscience will increase substantially in the applied setting.

Operational neuroscience provides a means to understand the brain in the context of the real world and to leverage our knowledge of the nervous system—from the cellular to the behavioral—in a way that maximizes the human potential. In reviewing the impact that operational neuroscience can offer the human factors, training, and operational research communities, the scientific literature presented in this section illustrates this vision and demonstrates uses of neuroscience to address critical challenges to the warfighter.

Section Papers

1. *"Converging Indicators for Assessing Individual Differences in Adaptation to Extreme Environments."* One of the first milestones in achieving the goal of operational neuroscience is to accurately assess the non-task related components that may affect brain activity and dynamics in the applied setting. In their paper, Patricia Cowings, William Toscano, Charles DeRoshia, Bruce Taylor, A'Liah Hines, Andrew Bright, and Anika Dodds (6) take this first step by recognizing the negative effects of the environment on crew health and performance after spaceflight. The authors call for the development and validation of assessment tools for evaluating these effects that are critical for operations in any extreme environment. In reviewing the existing literature from studies in both laboratory conditions as well as realistic environments, the authors weigh the importance of studying a wide spectrum of behavioral and physiological changes that occur under a battery of different conditions. They conclude that a multivariate approach to measure indicators of performance conducted si-

multaneous to self-report scores are the necessary foundation to any study designed to measure individual differences in operational efficiency.

2. *"The Effect of 24–40 Hours of Sleep Deprivation on the P300 Response to Auditory Target Stimuli."* Also in the category of non-task-related effects on cognition, the effect of sleep deprivation on performance is of great interest to the military research community. In their article, Gil Zukerman, Abraham Goldstein, and Harvey Babkoff (25) expand on prior literature by detailing the proposed reductive effects of sleep deprivation on the amplitude of the P300 in response to auditory stimuli. Using behavioral and electrophysiological measures, these authors investigate the potential effects of sleep deprivation on the P300 via circadian influences. They describe the findings that in their subject population ($n = 18$) no statistically significant difference in P300 amplitude was detected as a result of sleep deprivation or time of day. However, latency of the P300 increased by 27 ms following sleep deprivation ($p < 0.01$) and a significant interaction ($p < 0.05$) between sleep deprivation and circadian rhythm was found. The authors conclude that P300 latency can be used as a significant predictor of when subjects are sleep deprived, and that sleep deprivation has an additional negative effect on the ability to correctly categorize stimuli in discrimination tasks, particularly on tasks performed in late evening.
3. *"Neurophysiologic Methods to Measure Stress During Survival, Evasion, Resistance, and Escape Training."* As detailed in the discussion above, the application of neuroscience measures to the training environment is a central theme of investigation within the field of operational neuroscience. In their paper, Marc Taylor, Kenneth Sausen, Lilianne Mujica-Parodi, Eric Potterat, Matthew Yanagi, and Hyung Kim (21) examine methods for creating an accurate measure of the impact of operational stress on an individual. Using the Survival, Evasion, Resistance, and Escape (SERE) training module as a realistic analogue of stress imposed by war, captivity, and related events, the authors present a systems approach for creating a model of measurable stress behaviors, including cerebral, neuroendocrine, and cardiac changes. Linking these stressor components with neurophysiology-based investigative techniques (fMRI, eye-blink reflex, etc.) the authors present a review of these measures and describe how each might be used as a tool to predict and monitor stress reactivity, cognition, memory, and other key aspects of human performance during operational stress.
4. *"EEG Correlates of Task Engagement and Mental Workload in Vigilance, Learning and Memory Tasks."* Finally, it is clear that the collection of neurophysiological measures in realistic environments is at the heart of operational neuroscience. In order carry out that work, researchers must have access to reliable, robust measures to utilize in their particular task settings. In their paper, Chris Berka, Daniel Levendowski, Michelle Lumicao, Alan Yau, Gene Davis, and Vladimir Zivkovic (2) investigate the use of a deployable, non-invasive technique to collect EEG measures correlated with performance. In a study of 80 healthy subjects, Berka et al. recorded and analyzed EEG readings measuring engagement and workload over 1-s intervals during a series of cognitive tests. Their results indicated that engagement decreased over a 20-min vigilance test, and that both engagement and workload were significantly increased during the encoding period of verbal and image learning and memory tests when compared to recognition/recall. The authors' data, in conjunction with existing literature suggest that EEG-engagement reflects information gathering, visual processing, and allocation of attention, whereas EEG-workload increases with increasing working memory and during problem solving. The authors also provide preliminary evidence that second-by-second monitoring via EEG can reflect parameters of task performance.

Research Gaps

The field of neuroscience is continuing to grow daily due to rapid changes in genetics, imaging technology, and data processing. Despite this, the tools and techniques necessary to enable an understanding about the nature of the brain and behavior are still outside our grasp. Significant investments are still needed in measures of brain activity that will allow us the spatial and temporal resolution of clinical settings in the applied environment. As the papers presented in this section allude to, there is a great deal to learn about the nature of the brain and cognition in the operational setting. Continued research in operational neuroscience will help uncover some of the answers to the persistent questions raised in this volume, and only through multidisciplinary efforts can the field of neuroscience take the next leap forward. Regardless of the specific domain, operational neuroscience will help provide solutions and push the human potential to levels far beyond what is possible today.

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