Understanding Brain, Cognition, and Behavior in Complex Dynamic Environments

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Abstract. Many challenges remain for understanding how the human brain functions in complex dynamic environments. For example, how do we measure brain physiology of humans interacting in their natural environments where data acquisition systems are intrusive and environmental and biological artifacts severely confound brain source signals? How do we understand the full context within which the human brain is operating? How do we know which information is most meaningful to extract from the data? How can we best utilize that extracted information and what are the implications for human performance? The papers comprising this section address these questions from conceptual, technical, and applied perspectives. It is clearly seen that significant progress has been made since the inception of the Augmented Cognition program and that, to overcome these challenges, a continued multidisciplinary approach is required across basic and applied research from cognitive scientists, neuroscientists, computer scientists, and engineers.

Keywords: electroencephalography (EEG), natural environment, operational neuroscience, Augmented Cognition, cognitive engineering, human dimension.

1 Introduction

Over the past several decades, the field of neuroscience has made significant contributions to our understanding of human cognition. Neuroimaging, in particular, has unveiled a great deal more about the structure and function of the brain and how mental representations and behavior are generated. Much of this research has been conducted in controlled laboratory environments in which isolated auditory or visual stimuli are presented and simple behavioral responses are required. Moreover, such tightly controlled laboratory settings often study participants in acoustically and eletromagnetically shielded rooms while operating under conditions of minimal or highly restricted movement. Although it has advanced our basic understanding of how the brain functions within highly constrained environments, the extent to which controlled laboratory research generalizes to how the brain functions in complex and dynamic environments in the real world is currently not well understood. In fact, it may be argued that "laboratory studies conceived and interpreted in isolation from real-world experience may do far worse than fail to generalize back to the natural environment; they may *generate* fundamental misunderstandings …" [1; p. 177]. Furthermore, what

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we know about degeneracy and complexity of biological systems [2,3] suggests that the brain is capable of using its estimated quadrillion neural connections in different ways to accomplish the same task. Based on these concepts, it's likely that there are fundamental differences in how the human brain actually functions to control behavior when it is situated in ecologically valid environments (i.e., situated cognition) relative to that observed in highly controlled laboratory environments.

Because of the complexity of the brain and the natural world, and the inherent measurement challenges of recording neurocognitive activity in uncontrolled environments, we are only now beginning to understand how humans process information and interact in the real world. Ecological approaches [4,5] have for a long time advocated the need to focus on human, task, and environmental interactions to understand behavior in realistic settings. Over the past decade, these concepts have been extended to understanding the interactions between brain functions and operational environments [6-18]. Tools designed to examine these interactions have been and are continuing to rapidly advance through programs such as Augmented Cognition [16-18]. Much progress has been made in neurotechnology as evidenced by advances in sensor technologies [19,20], signal processing techniques such as independent component analysis [21-23], directed component analysis [24], and single-trial phase synchronization [25,26], as well as computational algorithms for classifying cognitive states [13-15,27-29] and brain-computer interfaces [30-32].

While these advancements are enabling preliminary insights into situated cognition, there exists a need to further advance such technologies and validate methodologies for conducting research in real-world environments. Sensor technologies and signal processing techniques have not yet matured to a level at which brain function can be reliably observed in naturalistic settings to the extent possible in laboratory settings [33]. While this goal may ultimately be untenable, science and technology are fast approaching toward this end. Due to challenges of experimental control, one approach is to integrate and synchronize multivariate data (e.g., physiological, behavioral, and contextual) and then apply data mining techniques to search for "hidden" relationships [22,34].

These advancing technologies and methods are expected to provide important insights into how people "think" about the information that they encounter – and how well they can translate that thinking into effective behavior. From an application standpoint, ensuring that people "think well" is non-trivial. The complicated nature of the human-task-environment interactions is seen in the analysis of military and industrial disasters, in which decision makers unsuccessfully interacted with equipment and other personnel in stressful, dynamic environments (e.g., see the shooting down of Iran Air flight 655 by the U.S. Navy in 1988 or the partial core meltdown of the nuclear reactor on Three Mile Island in 1979). Analysis of such disasters reveals that cognitive aspects of complex human-system interactions can have dramatic and unexpected consequences [35]. As the explosive advances in information and computing technologies that have occurred over the past several decades continue, and as the relationships in society become increasingly dynamic and nonlinear, it is expected that the nature of cognitive processing will continue to change from a model that primarily relies on people to one that involves a balance between people and technology.

As a consequence, it is expected that human-system performance in the real world will be largely dependent on how well such systems are cognitively engineered [10,34].

To highlight the state-of-the-art in neurotechnology, the current fundamental research gaps, and the potential benefits of advancing our understanding human cognition in operational environments, we have selected papers in several critical areas. The session starts with Stephen Whitlow presenting recent research on wireless, dry-sensor EEG-based workload classification conducted on dismounted soldiers during performance of military operations in urban terrain (MOUT). This paper frames the problems and illustrates the successes and issues of neurocognitive monitoring of ambulatory soldiers in the real-world. From that basic framework, the next two papers present cutting-edge hardware and software developments for mobile brain imaging. Chin-Teng Lin presents engineering advances of a wireless, dry sensor EEG system featuring micro-electrico-mechanical systems (MEMS) sensors with digital signal processing on a chip. Robert Frank introduces a novel real-time artifact mitigation algorithm based on a spatial filtering to direct the removal of biological artifacts from brain signals in EEG data. The following two papers extend the discussion from EEG to a more comprehensive multidimensional approach to understanding brain and behavior. Scott Makeig presents a new mobile brain/body imaging (MoBI) concept for integrating multisensory inputs such as eye, head, and body movements along with EEG and contextual data from behavior and the environment. Don Tucker then discusses data fusion and data mining approaches to creating and interpreting data sets that include eye- and head-tracking, high-density EEG, and system-based information and the challenges associated with data synchronization and integration. The final two papers in the session present the application of neurotechnology for enhancing our understanding of cognitive states of individuals in ecologically valid task environments. Ruey-Song Huang presents EEG correlates of driving performance based on time-frequency analysis of independent components derived from ICA and discusses implications for the design of human-computer interface design. Bradley Hatfield concludes the session by discussing a broad framework for understanding principles of brain function for highly skilled visuomotor performance. He also presents research on the effects of stress on performance and the application of a neurofeedback training program to enhance performance.

2 Session Papers

1. Whitlow, Mathan, Dorneich: "EEG-based Cognitive Workload Estimation of Mobile Soldiers in Training Missions." One of the most difficult problems facing scientists and engineers is to better understand human dimensions of performance in the real world, especially in complex dynamic environments in which soldiers perform. Whitlow and colleagues confronted this problem head-on by acquiring EEG data continuously from dismounted soldiers during training of military operations in urban environments (MOUT) using a six-channel, wireless, dry electrode EEG system (QUASAR, Inc.) fitted under the helmet. High and load cognitive workload periods were identified from a video log of soldiers performing various tasks throughout training during day and night operations, as rated by independent

observers and by the soldiers themselves immediately following the completion of each training mission, and statistical machine learning techniques were applied to the EEG spectra to determine classification accuracy. Results revealed 75-90% classification accuracy depending on duration of the temporal smoothing windows. Challenges posed by individual differences and dynamically changing tasks are discussed, as are implications for future research.

2. Lin, Ko, Chang, Wang, Chung, Jung: "Wearable & Wireless Brain-Computer Interface and Its Applications." Lin and colleagues introduce a new prototype, four-channel, mobile and wireless EEG system featuring miniature data acquisition circuitry and dry Micro-Electro-Mechanical System (MEMS) electrodes embedded in a headband. The system consists of a data acquisition (DAQ) unit, a wireless-transmission unit, and a real-time signal-processing unit. They also present research from their lab validating the system with participants performing a realistic lane-maintenance driving task in a virtual-reality-based dynamic driving simulator. Results verified that the system performed comparable to established wet-electrode systems. Challenges and future directions for application of this exciting new technology are discussed.
3. Luu, Frank, Kerick, Tucker: "Directed Components Analysis: An Analytic Method for the Removal of Biophysical Artifacts from EEG Data." Luu and colleagues introduce a new signal processing technique, directed components analysis (DCA), for removing biological artifacts from EEG data in real-time. DCA is a spatial filtering method that employs a spatial template to direct the selection of targeted artifacts, is computationally efficient, and can be applied online in real-time. In this paper they examine the effects of undersampling the scalp potential field on the ability of DCA to remove blink artifacts from event-related potential (ERP) data without distortion using high (128 channel) and low (32 channel) density recordings. The results revealed error fractions of .22 and .34 for high and low density recordings, respectively. Strengths and weaknesses of DCA are discussed with respect to alternative methods and future directions are also discussed.
4. Makeig: "Mind Monitoring via Mobile Brain-Body Imaging." Makeig and colleagues expand on existing concepts in brain-computer interface (BCI) design and application based on mobile brain/body imaging (MoBI) for brain/body interface (BBI). MoBI proposes a multisensory modeling approach (brain, eye-movement, body motion and environmental/contextual data integration) to cognitive state monitoring for application to a new, more robust brain/body interface (BBI). This approach extends existing brain-computer interface (BCI) designs by enabling the assessment of complex, natural behaviors in realistic environments and makes greater use of information embedded within the EEG signal (previous BCI systems underutilize information in the EEG; e.g., only one spectral band or time domain signal feature). Additionally, fundamental questions regarding individual differences, brain systems that effect BCI modulation, integration of multisensory inputs, and the effects of training on phasic and tonic brain states are discussed.
5. Tucker, Luu: "Operational Brain Dynamics: Data Fusion Technology for Neurophysiological, Behavioral, and Scenario Context Information in Operational Environments." One major challenge to understanding brain dynamics in operational environments is to be able to synchronize and integrate multiple sources of data from the individual, task, and environment in order to better understand the

operator's current state. Tucker and Luu present a state-of-the-art net-centric, distributed-parallel informatics architecture for increasing the bandwidth of the instrumentation and fused analysis of neurophysiological, behavioral, operational scenario events.

6. Huang, Jung, Makeig: "Tonic Changes in EEG Power Spectra During Simulated Driving." Huang and colleagues present research on the relation between brain activity patterns and driving performance. Independent component analysis (ICA) was applied to EEG data acquired from subjects during a simulated lane-maintenance driving task and time-frequency analysis was conducted on clusters of independent components. The results revealed that several clusters of independent component activities showed tonic elevation in alpha- and theta-band power spectral baseline as reaction time to lane-drift events increased, while other clusters showed broadband or delta-band increases. Implications of this research are discussed with respect to practical applications in human-machine interface/ interaction design.
7. Hatfield, Haufler, Contreras-Vidal: "Brain Processes and Neurofeedback for Performance Enhancement of Precision Motor Behavior." Understanding the how the brain adapts with training (i.e., neural plasticity), how it functions during highly skilled motor behavior, and how stress effects brain function and performance are interesting scientific endeavors with important potential implications for education and training. Hatfield and colleagues discuss a conceptual framework of psychomotor efficiency for motor skill learning and elite-level performance and review current research illustrating the effects of competitive stress on cortical perturbations and shooting performance. They also review new research on how neurofeedback training influences cortical dynamics and shooting performance. Finally, future directions are discussed with respect to the relevance of genetic influences and individual differences in brain function of skilled performers under stress and the role of social factors.

3 Summary

The presentations comprising this session represent advances in basic research and engineering of the hardware and software required for neurocognitive assessment in operational environments, as well as field research, applications and vision for future application. While this session has focused on the ecological principle of examining cognitive function in realistic settings, great progress is being made and will continue to be made through highly-controlled laboratory-based investigation. However, we must focus on converging laboratory and field research with cognitive engineering to ensure the development of system designs that present information to people in ways that enable greater comprehension in shorter durations without inducing undue cognitive demands; intuitive designs that decrease the need for training; and adaptive systems that understand a person's state and adjust training or augment the system accordingly.

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