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The Cognition and Neuroergonomics (CaN) Collaborative Technology Alliance (CTA): Scientific Vision, Approach, and Translational Paths

by Kelvin S. Oie, Kaleb McDowell, Jason Metcalfe, W. David Hairston, Scott Kerick, Tim Lee, and Scott Makeig

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The Cognition and Neuroergonomics (CaN) Collaborative Technology Alliance (CTA): Scientific Vision, Approach, and Translational Paths

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14. ABSTRACT

The Cognition and Neuroergonomics (CaN) Collaborative Technology Alliance (CTA) has recently been formed by the U.S. Army Research Laboratory (ARL) and a consortium of leading industry and academic research partners. The CaN CTA seeks to build upon our knowledge of neuroscience, human factors, psychology, and engineering to enhance our understanding of Soldier brain function and behavior in complex operational settings, assessed outside the confines of standard research laboratories. To do so, new approaches to neuroscientific inquiry are needed to overcome the scientific and technological barriers that have limited previous research efforts. This report discusses these barriers, and presents the overall CaN CTA scientific vision and approach to overcoming them, as well as describes three initial transitions that outline paths that will result in practical solutions to address Army problems and unmet needs.

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Contents

List of Figures v

List of Tables v

Preface vi

1. Introduction 1

1.1 The CaN CTA 3

2. Translational Science 5

2.1 Army Relevance 5

2.2 Scientific Barriers and Hurdles 6

2.3 The CaN CTA Scientific Vision 9

3. The CaN CTA Approach to Translational Science 12

3.1 Addressing Scientific Barriers to Enable Translational Science 12

3.2 Translational Science Within Specific Neurocognitive Performance Domains 23

4. Transitions 26

4.1 TE I: MoBI for Detecting Changes in Vehicle Operator Alertness and Performance Prediction 27

4.1.1 TE I. Background 27

4.1.2 TE I. Transition Barriers and Hurdles 28

4.1.3 TE I. Translational Timeline 29

4.1.4 TE I. Transitions 31

4.2 TE II. Advanced Tools for MoBI and Neurocognitive Performance Assessment 32

4.2.1 TE II. Background 32

4.2.2 TE II. Transition Barriers and Hurdles 33

4.2.3 TE II. Transitional Timeline 35

4.2.4 TE II. Transitions 38

4.3 TE III. Enhanced Design of High-information Multichannel Crew Stations 39

4.3.1 TE III. Background 39

4.3.2 TE III. Transition Barriers and Hurdles 43

4.3.3 TE III. Translational Timeline.....46
4.3.4 TE III. Transitions 49

5. References **50**

Appendix. Listing of Projects and Principal Investigators **57**

List of Symbols, Abbreviations, and Acronyms **59**

Distribution List **62**

List of Figures

Figure 1. A wearable and wireless dry-electrode (WWD) EEG system that features dry MEMS EEG sensors (lower left), low-power signal acquisition, amplification and digitization, wireless telemetry (upper left), with online signal processing. 16

Figure 2. Through-the-hair dry electrode design. A yet newer (07/09), low-cost ($0.50U.S.) design (not shown) has "fingers" that make varying height and angle contacts with the scalp. 17

Figure 3. Translational timeline depicting expected progress in TE I. 30

Figure 4. Translational timeline depicting expected progress in TE II. 36

Figure 5. Example of crew station technology developed to optimize Soldier workload and provide the ability to conduct mission planning; route planning; reconnaissance, surveillance, and target acquisition (RSTA); and fire control capabilities. The crew station WMI software is fully configurable (up to six possible independent screens may be displayed simultaneously), portable (between crew stations), and interoperable. Here, two crew stations are shown as mounted on a large 6 DOF motion simulator located at TARDEC.....40

Figure 6. Translational timeline depicting expected progress in TE III. 47

List of Tables

Table A-1. Projects and principal investigators. 57

Preface

Meeting the needs of the Army's Future Force requires ongoing research investments that also support the rapid transition of innovative technologies from cutting-edge basic research to fieldable technological solutions. As a means for enabling this process, the Army must bring together world-class research and development talent and focus it on Army-specific technology objectives for application to Army needs.

A Collaborative Technology Alliance (CTA) is a partnership among Army laboratories and centers, private industry, and academia. Active collaboration among these three components is a key element of the CTA concept, with each bringing distinctly different approaches, perspectives, and capabilities: academic research laboratories are the country's storehouse of basic science innovation; industrial partners have unique capabilities and relationships that are needed to leverage existing research results into technology transition; and Army scientists and engineers bring both research skills and a Soldier-centric focus to keep programs oriented toward solving complex Army technology problems. In this way, CTAs are comprised of multidisciplinary teams that are generating the technological advances needed to meet the needs of the Future Force.

The U.S. Army Research Laboratory (ARL) has a history of successful CTA collaborations dating back over a decade, including five completed CTA programs. The Advanced Decision Architectures CTA, which designed, tested, and transitioned new computer science innovations to facilitate better Soldier understanding and situational understanding; the Advanced Sensors CTA, which developed affordable sensors to provide continuous situational awareness; rapid, precise discrimination and targeting; and the ability to sense the environment for rapid navigation and defense; the Communications and Networks CTA, which developed technologies to enable a fully mobile, fully communicating, agile, situationally aware, and survivable, lightweight force, through advanced wireless networks across multiple, heterogeneous agents under severe bandwidth, energy, security, and operational constraints; the Power and Energy CTA, which advanced fundamental sciences and understandings of efficient, lightweight, compact power and propulsion technologies for the dismounted Soldier, vehicles, and robotic platforms of the future Army; and finally, the Robotics CTA, which researched core technologies to support Army autonomous vehicle goals and advancing the state-of-the-art in perception technologies, intelligent controls, and human-machine interfaces.

Now, the Cognition and Neuroergonomics (CaN) CTA seeks to continue the successes of previous collaborative work involving Government, industry, and academia. The CaN CTA has been established to address the development of fundamental translational principles, i.e., principles governing the application of neuroscience-based research and theory to complex operational settings. The Alliance will be building upon and leverage the massive worldwide

research and technology development efforts in the cognitive neurosciences. For example, the popular Web site scimagojr.com reports that there have been over 400,000 citable articles published in the neurosciences worldwide in the period between 1996 and 2010, with articles appearing in more than 300 peer-reviewed neuroscience journals. In addition, the National Industrial Organization reports an over $140 billion USD annual investment in neurotechnologies, and the publication of articles related to brain-computer interface has witnessed nearly exponential growth over the past decade.

Exciting new developments in sensor technologies, statistical modeling approaches, and computational analysis capabilities are bringing new methodological and paradigmatic changes that are consistent with the growing appreciation of the fundamental need to study human cognitive behavior under real-world conditions. Furthering the development and application of these technologies, methods, and approaches are foundational to the vision and the approach adopted by the CaN CTA, which is articulated in this document. Realizing this vision through the focused research and development efforts planned within the CaN CTA has the potential to achieve ground-breaking advances in Soldier-System design improvements and position the Army as a world-wide leader in the neuroscience research and neurotechnology development communities.

Other Government agencies are invited to join this Alliance, contribute their technical expertise and personnel, and participate fully in collaborative research efforts under the CaN CTA. The intellectual synergies established through such collaboration, including the sharing of equipment and facilities to promote efficiencies, will create a critical mass of private sector and Government scientists and engineers focused on solving the military technology challenges impacting Soldier neurocognitive performance, as well as supporting and stimulating dual-use applications of this research and technology to benefit commercial use. To achieve this, the CaN CTA will implement computational modeling, and will conduct and link neuroscience-based research from multiple levels to produce advances in fundamental science and technology, demonstrate and transition technology, and develop research demonstrators for Warfighter experimentation.

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1. Introduction

Difficulties experienced as U.S. forces attempt to identify and neutralize the threats associated with the evolving security context have inspired the Army to reconsider, at a fundamental level, the capabilities and readiness of its personnel and materiel resources (Geren and Casey, 2008; Speakes and Martin, 2008). Imperatives to prepare and transform the Army to meet the demands of the modern strategic environment have placed science and technology in a prominent position.

Enabling technology advances are enhancing Soldier-system performance and expanding operational capabilities, however, these advances can also intensify the need to assess the Soldier's ability to perform tasks under complex, dynamic, and time-pressured operational conditions. Technological advances, particularly in sensor deployment, information bandwidth, and automation, coupled with economic and political realities, will continue to place more and more responsibility on fast, distributed, and effectively independent decisions by solo or small groups of Soldiers who control ever more potent defensive and offensive assets. Under such circumstances, Soldier cognitive failures in comprehension and decision making based on an ever more complex data stream may become a critical bottleneck in Army defensive and offensive capabilities. Indeed, both failures to act and imprudent reactions can have high costs in terms of mission success, human suffering, and sociopolitical perception.

It thus becomes increasingly important that Army systems integrate knowledge of, as well as actively enhance, operator cognitive state and reactions to events. Towards this end, neuroscience-based approaches have the potential to provide revolutionary advances to foster practical solutions to address Army needs (cf., National Research Council, 2009). Recent progress in the neurosciences has greatly advanced our knowledge of how brain function underlies behavior, providing our modern scientific foundations for understanding how we sense, perceive, and interact with the external world; an understanding that, if properly leveraged, can lead to improved capacity for integrating human neurocognitive function with Army system design and performance.

The Cognition and Neuroergonomics (CaN) Collaborative Technology Alliance (CTA) has recently been formed by the U.S. Army Research Laboratory (ARL) and a consortium of leading industry and academic research partners to address these challenges. Here, the term "neuroergonomics" is used as originally proposed and defined by Parasuraman (2003) as "the study of the brain and body at work," and specified for military applications as "operational neuroergonomics" within the CaN CTA as building upon neuroscience, human factors, psychology, and engineering to enhance our understanding of Soldier brain function and behavior in complex operational settings, assessed outside the confines of standard research laboratories.

However, applying basic research in cognitive science to the understandings of Soldier neurocognitive behavior that are needed to enable a neuroscience-based approach to systems design is non-trivial. Several scientific and technological barriers have placed significant limitations on the impact of previous research efforts (see section 2.2 for more detailed discussions of each scientific barrier):

B.1 The restriction of experimental designs to highly controlled and impoverished stimulus/response paradigms and environments

B.2 The lack of portable, user-acceptable (e.g., comfortably wearable), and robust systems for routinely monitoring brain and body dynamics

B.3 The failure to record the whole of physical, mental, and physiological behavior that the brain controls, and the physical and socio-cultural effects of the environment that impact brain function, in sufficient detail and across a sufficient breadth of circumstances

B.4 The lack of mathematical modeling methods to find statistical relationships among the moment-to-moment variations in environmental, behavioral, and functional brain dynamics

B.5 The lack of sufficient data archives and resources to systematically study relationships between individualized models derived for cognitive monitoring and individual differences in performance, cognitive ability, and personality, relationships that could optimize performance of cognitive monitoring systems while lowering requirements for collecting individual subject training data

The limitations that these barriers impose have resulted in a lack of a clear working understanding of how the human brain functions when faced with real-world tasks in real-world operational settings, as opposed to how it works in highly constrained tasks in highly controlled laboratory settings. In turn, this has meant that previous systems development approaches and methods for technological advancement cannot adequately account for the full spectrum of capabilities and limitations of human neurocognitive function.

Within this context, the scientific vision for the CaN CTA has been derived from an ecological perspective, as well as concepts of embodied or situated cognition, that considers humans to be active agents embedded in a complex and dynamic environment. Cognitive processes, and the brain function that underlies them, have evolved to optimize the outcome of our behaviors within our physical and socio-cultural environments. Acceptance of this position imposes specific constraints on our methodological decisions; in particular, this understanding indicates that it is literally impossible to understand natural, motivated behavior in artificial scenarios that divorce the individual from their context.

New approaches to neuroscientific inquiry are therefore needed to overcome the scientific and technological barriers that have limited previous research efforts. The approach taken by the CaN CTA aims to address these barriers directly through the following:

- Development of experimental paradigms that capture the unfolding nature of multisensory stimulus streams experienced in real-world environments
- Development and employment of novel, wearable sensor suites for monitoring brain and body dynamics during naturalistic behavior as well as the software for integrating brain, sensory and behavioral monitoring systems
- Acquisition and processing of high-dimensional datasets that characterize physical, mental, and physiological behavior, as well as its environmental context, in sufficient detail across a sufficient breadth of circumstances
- Discovery of models and novel methods for the identification and interpretation of statistical relationships among high-dimensional data sets characterizing the dynamics of environment, behavior, and brain function during complex task performance
- The acquisition and analysis of data from a large number of individuals allowing characterization of inter- and intra-individual variation in order to systematically study the relationships between individualized models derived for cognitive monitoring and individual differences in performance, cognitive ability, and personality

Success within this approach, in turn, is envisioned to lead to the establishment of principles on which to base advances in neuroscience in terms of translating fundamental research to military relevant domains; that is, to establish and articulate fundamental translational principles. These principles are envisioned to guide the development of technology solutions that work in harmony with the capabilities and limitations of the human nervous system as situated within its dynamic, complex environment.

1.1 The CaN CTA

The purpose of this report is to present the overall CaN CTA scientific vision and approach, as well as describe the three initial transitions that outline paths that will result in practical solutions that address particular Army problems or unmet needs.

In the remainder of this section, we briefly describe the organization and organization of the CaN CTA program. The research program for the CaN CTA has been organized into three technical areas (TAs) that are strongly interconnected, comprising a highly integrated research and conceptual approach.

TA1. Neurocognitive Performance: Research efforts under this area are designed to ascertain key "signatures" of how Soldier neurocognitive state (i.e., emotional, perceptual-cognitive, physical, and physiological) varies in the face of the sensory, perceptual, and cognitive demands of the operational environment.

TA2. Advanced Computational Approaches: Research within this second area will provide novel computational, statistical modeling, and data visualization techniques for the extraction of the signatures of Soldier neurocognitive performance, including novel analytic/algorithmic approaches to the individualized assessment of Soldier neurocognitive state and performance.

TA3. Neurotechnologies: The third area focuses on the research underlying cutting-edge technologies for the real-time recording and analysis of environmental, behavioral, and functional brain dynamics, and on techniques for exploiting natural human neurocognitive function in technological solutions that enhance Soldier-system performance and safety.

The initial membership of the CaN CTA represents a truly international and multidisciplinary team, and comprises membership from the following industry and academic institutions:

1. DCS Corporation (DCS), Alexandria, VA, USA
2. University of California San Diego (UCSD), San Diego, CA, USA
3. University of Michigan, Ann Arbor, MI, USA
4. University of Texas San Antonio (UTSA), San Antonio, TX, USA
5. National Chiao Tung University (NCTU), Hsinchu, Taiwan
6. University of Osnabrück, Osnabrück, Germany

Additionally, the CaN CTA is pleased to welcome three new collaborating organizations, as well as additional research partners at the University of Michigan, whose research efforts as sub-awardees to the Alliance will bring new perspectives and approaches to addressing the critical challenges being addressed by CTA researchers:

1. Columbia University, New York, NY, USA
2. University of California Santa Barbara (UCSB), Santa Barbara, CA, USA
3. University of Pittsburgh, Pittsburgh, PA, USA

A listing of specific projects and their respective principal investigators is located in the appendix.

2. Translational Science

2.1 Army Relevance

Future Force concepts include the goal of establishing and maintaining information dominance by implementing advanced information and communications technologies in a massively interconnected, networked battlefield, including an increased reliance on unmanned assets while, at the same time, decreasing crew sizes to minimize the number of Soldiers in harm's way (Speakes and Martin, 2008). Attempting to preserve operational capabilities while decreasing local crew sizes and distributing tasking across a broad network of non co-located teams will require the future combat Soldier to adopt a significantly modified and quite demanding role. For example, as envisioned under Future Force concepts, it is possible that an individual Soldier will be responsible for concurrent monitoring of data from unattended ground sensors, maintenance of intra- and extra-vehicular communications, operation of non-line-of-sight munitions, as well as execution of direct, remote or supervisory control over a vehicle or a number of other unmanned ground and/or aerial assets (Fetterman and Plushnik, 2007).

What is more, due to pervasive threats from enemies who employ unconventional tactics, such as improvised explosive devices (IEDs), Army operations will increasingly be conducted either from within vehicles that are completely enclosed in armor or from locations remote to the battlefront. Therefore, both mounted and dismounted Soldiers will execute most tasks involving interactions with the battlefield through a variety of computerized control and visualization systems (Keller, 2004), rather than based on information from first-person immersion in the immediate zone of conflict.

The fact that such operations will inevitably be conducted within a dynamic, multidimensional urban context, where battles tend to unfold on shorter temporal and spatial scales, only serves to increase the level of demand, threat and risk to U.S. troops. Because of limitations on both technology and human function within such complex operational environments, performance decrements are a chief concern of those examining issues related to the development and implementation of technologies that can enhance the function of integrated, human-machine, sociotechnical systems (Cowings, Toscano, DeRoshia, and Tauson, 2001; Endsley and Kaber, 1999; McDowell, Oie, Tierney, and Flascher, 2007; Metcalfe, Davis, Tauson, and McDowell, 2008; Stanton and Marsden, 1997; Stanton and Young, 1998; and van Erp and Padmos, 2003).

The skilled cognitive and sensorimotor performance that underlies effective mission use of human-machine, sociotechnical systems is clearly organized at the level of the nervous system. Thus, in order to develop neuroscience-based systems to meet critical Army needs, the CaN CTA program has been designed to provide the systematic exploration of the neural underpinnings of

Soldier-system performance needed to elucidate new understandings of human neurocognitive function as situated within the complex, dynamic task environments that typify Army operations.

The advances to be gained from the CaN CTA program hold the potential for radical and revolutionary changes to systems design and development to enhance Soldier-system performance: The improved understandings of Soldier neurocognitive state and performance within the operational environment that are the aim of the Neurocognitive Performance research area will provide the fundamental knowledge required to enable a systems design approach that can work in harmony with human brain function. The computational models and data analytic methods developed under the Advanced Computational Approaches research area will provide Army researchers and engineers not only with new approaches to understanding, but also with the tools to develop automated systems and intelligent architectures that integrate real-time knowledge of Soldier neurocognitive state to complement and supplement Soldier abilities. Moreover, the technologies and tools for functional brain imaging-based detection of Soldier cognitive performance that will be developed through the third Neurotechnologies research area, as well as planned CaN CTA transition efforts, have far-reaching translational potential, not only within Army and Joint service materiel, training, medical, and testing domains, but also throughout the civilian science and technology (S&T) community.

Finally, *the overarching aim of the research to be conducted by the CaN CTA is to develop and demonstrate principles that govern the translation of research in cognitive neuroscience from basic to applied levels* and that can guide efforts to best support future Soldier-system technological development. Such principles must be both grounded in data and theory from basic cognitive neuroscience research and reflective of a deep understanding of how the human brain, body, and sensory systems work in concert to accomplish tasks within militarily-relevant operational contexts. Once established, these translational principles will be fundamental in driving and speeding the transition of Army basic and applied research efforts into high-impact, mission-enabling technologies.

2.2 Scientific Barriers and Hurdles

The main problem that the CaN CTA is addressing is that mission-enabling technologies and the methods for technological advancement do not adequately account for the capabilities and the limitations of human neurocognitive function. In large part, this state of affairs can be attributed to the S&T community lacking the theory and tools required to provide a clear working understanding of how the human brain functions when faced with complex real-world tasks in real-world operational settings, as opposed to how it works in highly controlled experiments in highly constrained laboratory settings. To fully understand Soldier neurocognitive performance in a manner that can support a neuroscience-based systems design approach, it is critical to directly study and precisely quantify the natural interactions among Soldier brain, behavioral, sensory, and performance dynamics as situated within complex task environments.

Five conceptual and technological limitations have thus far precluded our capability to leverage advanced technologies to address the lack of knowledge regarding human brain function as situated in the real world.

B.1 The restriction of experimental designs to highly controlled and impoverished stimulus/response paradigms and environments.

Both human behavior and the environment within which it unfolds are rich, dynamic, and complex. To harness the complex dynamics of environment and behavior, the scientific study of human performance has traditionally employed paradigms that aimed at simplicity in both stimuli and measured behavior. The vast cacophony of sounds that makes up the auditory environment, for example, has typically been reduced to single frequency, limited duration "beeps," while the rich, continuous array of visual contours, colors, and contrasts present in the natural visual environment has typically been replaced in laboratory experiments with spatially, temporally isolated simple patterns, gradients, or light flashes with stereotyped and tightly controlled properties (contrast, luminance, color, etc.). Motor behavior, in like fashion, has often been studied through single joint (e.g., button press), single limb (e.g., point and reach), or simplified whole-body (e.g., standing) actions. However, as discussed above, to understand natural behavior, it is critically important to migrate research from such controlled tasks and environments into those that reflect the complex interactions between natural behavior and the natural sensory world within which it is embedded. Perhaps the most potent evidence for such a position is to be found in arguments articulating a fundamental disconnect between observations in laboratory settings and those obtained from within a real-world context (Kingstone et al., 2008); that is, what is seen in the laboratory may not (and often does not) necessarily represent how the brain actually functions when presented with a real task and situated in a real-world setting (Foerde et al., 2006).

B.2 The lack of portable, user-acceptable (e.g., comfortably wearable), and robust systems for monitoring brain and body dynamics.

If we aim to observe, in a precisely quantifiable fashion, humans performing realistic tasks as naturally as possible within operationally relevant contexts, then improvements must be made to current methods of instrumentation. That is, in order to allow for reasonable inference regarding natural behavior in such contexts, human participants must be allowed to behave as they would, without being encumbered by extensive arrays of sensors, leads, power supplies, and processing units. At the same time, a considerable array of sensors is necessary to capture sufficiently precise and detailed information regarding brain and behavioral dynamics, especially to avoid confounds due to the behaviors being performed as well as environmental fluctuations that may introduce variable levels of artifact into the data. Thus, an ideal monitoring system would be comfortably wearable for participants as they perform natural behavior and yet would also contain a complete and robust array of sensors to provide the detail necessary for understanding true, contextually situated behavior.

B.3 The failure to record the whole of physical, mental, and physiological behavior that the brain controls, and the physical and socio-cultural effects of the environment that impact brain function, in sufficient detail and across a sufficient breadth of circumstances.

The evolution of the human brain has been shaped by the need to adaptively optimize the outcome of our behavior within the context of our three-dimensional (3-D) environment. Imaging studies show that human brain systems that organize our decision making involve the same systems as those that organize our motor behavior (Rizzolatti et al., 2002). Likewise, the ways we think about and communicate abstract concepts are often firmly based in our bodily experience in the 3-D world (e.g., "Let's get in touch."… 'Time marches on."…). The conceptual meaning of this argument is that brain function cannot be understood in isolation from the behavior that is to be controlled and the context within which it is to be controlled. Yet the traditional enterprise of science has followed a course that has led to a fractionation of our understanding of the whole of human behavior into relatively disjoint pieces falling within the respective purviews of individual academic domains. Specific brain function (e.g., the behavior of neurons and neural circuits), for example, has fallen under the large umbrella of neuroscience, while emergent properties of neural function (e.g., cognition, perception, etc.) have traditionally been studied within the cognitive and psychological sciences and, finally, physical actions themselves have been the subject of movement science and biomechanics. Although broader consideration of the whole ensemble of behavior, particularly relations between motor and cognitive aspects, has begun to appear more frequently in the literature (c.f. Middleton and Strick, 2000; Rosenbaum, 2005), it remains a fundamental challenge to build the database of collective knowledge regarding how the brain works while it is actively organizing and executing cognitive and physical action within the natural environment and across a set of tasks representative of the natural functional repertoire of the skilled human making strategic decisions based on accumulating streams of natural sensory data.

B.4 The lack of mathematical modeling methods and software to find statistical relationships between moment-to-moment variations in environmental, behavioral, and functional brain dynamic recordings.

Beyond the acquisition of data sufficient to draw inferences regarding natural human behavior within rich, real-world settings is the need for analytic tools to detect and identify patterns and relationships within those data. For example, the focus of most traditional analyses in psychology, biodynamics, and neuroscience has been on modeling repeatable and (often) passive interactions allowing the use of simple response averaging methods and second-order statistics. Currently, however, there are increasing needs to model nonlinear interactions in biological and cognitive systems, and develop methods to identify complex patterns in huge datasets using new information-based statistical methods. Consider Soldiers and commanders faced with unfolding challenges in complex operational environments who need to make operational decisions by interacting with multiple streams of incomplete and possibly misleading information. Optimum models of their learning and decision-making processes cannot simply combine separate

psychological, biodynamic, and neurodynamic models, as these all interact in complex (often nonlinear) ways. True understanding of human behavioral decision making under stress in complex operational environments, therefore, requires direct, quantitative, and model-based study of brain, behavioral, sensory, and performance dynamics, based on their simultaneous measurement in complex, operationally relevant environments and their joint analysis accounting for their higher-order interactions and relations.

B.5 The lack of sufficient data archives and resources to systematically study relationships between individualized models derived for cognitive monitoring and individual differences in performance, cognitive ability, and personality, relationships that could optimize performance of cognitive monitoring systems while lowering requirements for collecting individual subject training data.

Typical studies of human cognitive function using brain imaging collect data from 10–40 subjects with goals of (1) determining a population mean and variance, the variability in the measures of interest thereby assumed to be distributed in a Gaussian manner across the subject population, or (2) determining the difference between two such subject group means with, most often, Gaussianity and equal variances assumed for both groups. However, increasingly cognitive, brain morphogenic, and neurogenetic studies reveal fine differences in cognitive abilities and style that limit overall performance of human-machine systems that do not adapt themselves to individual operator proclivities and characteristics. Development of principles governing construction of individually adapted human-system interfaces is the principal aim of the CaN CTA.

2.3 The CaN CTA Scientific Vision

Across the broad spectrum of Army operations, Soldiers and commanders are expected to continually make decisions based on distributions of information across various temporal and spatial scales that they acquire by active attention to and interaction with multiple audio, video, and/or tactile information streams. Successful decision making in such environments requires operator recognition of the overall significance of accumulating information so as to continuously maintain situational awareness and answer operationally relevant command questions posed by events. Enabling optimized decision making defined in this manner requires an understanding of the intimate relationships between the Soldier and the operational environment as mediated by physiology, cognition, and overt behavior.

We posit that applying basic research in cognitive neuroscience to understanding Soldier neurocognitive behavior within these dynamic, complex environments will be most fruitful if it can continually and successfully monitor and interpret brain/behavioral processes, indexing (1) the depth, distribution, and shifting of operator attention; (2) the operator's appraisal of the significance of incoming information; (3) the emotional context (e.g., motivation and intent) of the operator's actions; and (4) the impact of physiological state (e.g., fatigue, stress, arousal) on cognitive and motor performance. In turn, such understandings are required to develop systems

that can exploit the natural properties of human neurocognitive and behavioral function to compliment and reinforce both individual and group operator abilities under dynamic and high information loads, as well as under circumstances of multiple objectives with differing levels of risk and reward. In other words, these understandings are needed to enable the design and development of systems whose ultimate purpose is to enhance Soldier-system capabilities to more effectively meet mission-critical demands.

Objectives such as these make observing and modeling how distributed brain processes support natural, active, and ever-varying behavior and cognition perhaps the most important challenge to successful translation of principles and methods from cognitive neuroscience. As articulated in ecological psychology and, in particular, in Gibson's (1979) *Theory of Affordances*, humans are active agents, continually engaged in actively attempting to fulfill their needs and desires within a complex and dynamic environment, often in concert and/or competition with other human, animal, and mechanical agents. Such influences and constraints have served to shape the evolution of the human brain by means of optimizing *the outcome of our behavior*.

At the same time, concepts tied together under the terms "embodied cognition" and/or "situated cognition" have become increasingly important in cognitive science and neuroscience. In a similar fashion, these concepts have been formed around the view that cognitive processes have evolved to optimize the outcome of our body-based behavior within our 3-D environment (Anderson, 2003; Clark, 1999; Garbarini and Adenzato, 2004). Key principles, or assumptions, include the following:

- *Perception and cognition support action.* A primary function of human perception is to assist motor control (Churchland et al., 1994; Reed, 1982). For example, the dorsal visual pathway directly supports visually guided actions such as grasping (Goodale and Milner, 1992). In monkeys and humans, motor neurons involved in controlling tools are active when pictures of tool use are viewed, even in the absence of overt motor actions or planning (Rizzolatti and Arbib, 1998).
- *Cognition is situated and time-pressured.* New information is integrated into our continually evolving cognitive environment, allowing us to adapt to and predict how events in our current environment may be influenced by our actions. Action-motivating events typically require timely, environment- and situation-appropriate action selection.
- *We actively interact with our environment to gain and hold situational awareness.* Our typical feeling that we "can see everything" around us rests on the feeling that what we see gives us enough information to know where to actively look for further information, when and if it becomes of interest. To further reduce our brain memory and processing load, we actively manipulate our environment.

- *Features of our environment are integrated into our cognitive system.* Our brain's body image extends beyond our physical body (Maravita and Iriki, 2004). For example, a tennis player's racket becomes an integral part of the player's brain/body "action system" (Reed, 1982), influencing the environment (the ball) to shape future events (the opponent's return).
- *Our imagination and abstract cognition are also bodily experience based.* Even imaginative and abstract cognition, independent of direct physical interaction with the environment, are body-based. For instance, sub-vocal rehearsal of contents in verbal working memory involves the same brain structures used for speech perception and production (Wilson, 2001), and imagining limb movements produces activity in the same brain areas involved in producing the actual movements. We interpret "abstract" linguistic metaphors and even abstract mathematical entities within ("as-if") virtual environments, such as when we "look forward" to the future, or imagine "the number line" (Núnez, 2006). Emotions may similarly involve somatic "as-if" states and events (Damasio et al., 2000).

Acceptance of these principles imposes particular constraints on the methodological decisions one must make when attempting to understand natural behavior in realistic environments. In particular, such concepts dictate that it is literally impossible to understand natural, motivated behavior in artificial scenarios and situations that divorce the individual from the context. In short, the reductionist paradigms that have thus far defined the "normal science" behind studies of human behavior provide information that is impoverished to the extent that the true nature of human performance appears intractable. Indeed, recent findings have demonstrated the importance of context in the differential engagement of neural resources during task performance (Foerde et al., 2006), supporting the idea that laboratory-based studies isolated from real-world experience may generate fundamental misunderstandings of the underlying principles being investigated (cf., Kingstone et al., 2008). Therefore, it is incumbent upon cognitive neuroscience to more adequately address the multiple hitherto unanswered questions of how distributed brain dynamics support complex, motivated actions within dynamic and only partially predictable real-world operational contexts.

True understanding of human behavioral decision making under stress in complex operational environments, therefore, requires direct study of the interactions among brain, behavioral, sensory, and performance dynamics in the context of task and environmental dynamics, based on their simultaneous measurement and joint analysis. In other words, cognitive neuroscience must develop new approaches to augment traditional ones that have largely divorced human behavior from the richness of its physical instantiation and context in order to represent it through the activity of a few neural populations in the cerebral cortex. These new approaches—both in terms of experimental paradigms and data analytic methodologies—must, as much as possible, mine the full spectrum of information available throughout the natural behavioral context for insights into fundamental neural principles that guide the organization of motivated action in real-world environments.

3. The CaN CTA Approach to Translational Science

Providing solutions to enhance neurocognitive human-system performance demands new approaches to basic science. Here we outline such an approach that identifies and develops fundamental principles translating cognitive neuroscience-based theory and observations to enabling technologies that enhance performance in militarily-relevant environments. Specifically, the CaN CTA research program aims to develop neuroscience-based principles that focus on how best to assist people to operate in complex, mixed-initiative system environments in which dynamic, complex information streams must be integrated across multiple spatial and temporal scales. The CaN CTA approach focuses on two factors: first, we directly address the scientific barriers outlined in section 2.2 to enable translational science; and second, we execute translational science within specific neurocognitive performance domains.

3.1 Addressing Scientific Barriers to Enable Translational Science

The CaN CTA will adopt an approach that directly addresses the five scientific and technical challenges identified in section 2.2.

B.1 Addressing the restriction of experimental designs to highly controlled and impoverished stimulus/response paradigms and environments.

Despite the advances obtained through the use of functional neuroimaging modalities over the past few decades, the physical and temporal constraints of technologies such as functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) have severely limited the scope of brain imaging during production of naturally motivated motor behavior, e.g., behavior involving whole body motion in normal 3-D environments. Thus, the use of such methods has forced investigators to observe neural function separate from its natural behavioral context.

It is our position that, currently, electroencephalography (EEG) is the only brain imaging modality that involves sensors light enough and low-powered enough to allow near-complete freedom of movement of the head and body with sufficient time resolution to record brain activity on the time scale of natural behavior. Therefore, EEG is the clear modality of choice for brain imaging of humans performing tasks involving natural movements in real-world operational environments.

Unfortunately, because of how EEG has traditionally been used to study neurocognitive function, limitations in its method of analysis has forced investigators to make trade-offs in terms of the fidelity and nature of behavior observed. In particular, traditional EEG paradigms severely restrict body, head, and eye movements of participants—largely out of fear of introducing non-brain artifacts into the EEG data records. In traditional EEG experiments, researchers have

typically measured only minimal participant behaviors; usually stereotyped button press responses to a limited set of discrete, temporally distinct, and suddenly presented stimuli. Because of the perceived difficulty of separating brain EEG data from non-brain artifacts, participants in such EEG experiments have been asked to sit still, suppressing or minimizing natural eye and head movements, waiting for stimulus onsets and then making relatively infrequent responses involving minimal limb movements (typically, pressing finger "microswitches") to convey their selections from among a discrete, limited, and artificial range of choices.

In well-established psychophysiology paradigms, simple EEG response averages that are time-locked to events in a number of *a priori* defined categories are then extracted from the brain data, reducing its complexity to a few averaged traces that are further collapsed into an even smaller table of peak amplitudes and latencies. Researchers then look for reliable relationships between these few summary values and a single behavioral dependent variable (e.g., the button the participant chose to press in each trial).

This approach essentially attempts to reduce the complexity of the recorded EEG dynamics (now easily recorded with a bandwidth of a million or more bits per second) to near the bandwidth of the recorded behavior (typically less than one button selection per second) by averaging across epochs time-locked to sets of events assumed to have similar brain dynamic consequences. Yet, given the complexity and marked moment-to-moment variability of human EEG dynamics, as well as the brain's central role in optimizing the outcome of behavior in the face of ever-changing physical and cognitive circumstances, it is unlikely that this reductionist, *a priori* approach will yield further high-payoff advances in understanding how distributed brain dynamics support natural operator behavior and processing of real-world operational environments.

From a mathematical point of view, then, the basic problem outlined above is that complex functional relationships between two or more high-dimensional and highly variable signals (e.g., brain dynamics and overt behavior) cannot be well characterized by constraining each to a few average measures and then comparing them. Rather, we argue that what is needed is a new and radically different approach incorporating better, higher fidelity recording and modeling of the full spectrum of information regarding relationships between neural and physiologic function, cognition, and overt behavior.

The approach being taken within the CaN CTA program is, therefore, to combine data from multiple, data-intensive sources so that the information latent in the observed brain/body/system dynamics may be identified as described above. The CaN CTA research then intends to develop novel computational and mathematical modeling methods to discover functional and statistically reliable relationships between simultaneously recorded brain, behavioral, and sensory dynamics. Important issues to be addressed are how to extract information that is invariant, stable, and robust to changes and/or degradation of the monitoring environment. Further, we want to be

proactive in enhancing the operator's cognitive and perceptive abilities, not reactive after the fact. For example, we want to predict when a human operator is likely to experience cognitive overload or incapacity prior to or at time of its first occurrence. Also, we would like to identify immediately when an operator has hastily made a command decision (e.g., by button press) that the operator now regrets.

To approach the richness and multidimensional variety of Soldier experience in relevant operational environments, Simulation and Demonstration phase experiment tasks will be complex. In particular, they will require operators to integrate information across multiple streams in different modalities. Operators will thus be required to continually ask themselves, *"To which information channel should I attend now to best maintain my awareness of the operational situation? Should I actively query or redirect any information channels? Do I have information I should I send my commanders and/or remote team members? Do I need to make a command decision to direct remote team members? If so, what decision?"*

The main Command Environment Simulator (CES) experiment to be conducted at the of UCSD may, for instance, involve an extended operational game space in which ally, foe, and indifferent agents will move and act. For example, in an urban conflict simulation, unnumbered, autonomous competitive agents (foes) may enter the 3-D game space (an urban neighborhood) at different rates of speed under stochastic control. Numbered, semi-autonomous cooperative agents (allies) respond to the commands of the operator stationed in a home vehicle command post. The operator may decide to order an ally to move so as to neutralize the advance of a foe. The operator will see displays showing simulated views from
(1) video cameras on the vehicle; (2) a (slowly) movable robot video camera; and (3) a (slowly) movable overhead still camera drone. The operator will receive speech communications from allies and occasionally from an off-map commander.

In the scenario thus described, the operator's task would be to position allies so as to neutralize threats from moving foes. The visual displays (vehicle, robot, drone) would each give spatially limited egocentric and allocentric views of the operational space on different spatial (distance) and temporal (update rate) scales. Speech communications from allies about foe locations and movements would either be given either from an egocentric perspective ("Foe approaching quickly") or an allocentric perspective ("Foe moving west slowly"), and would sometimes be misleading or inaccurate. Location-based speech communications would be egocentric ("I am two blocks north and one block east of you, facing west"). Spatial auditory and vibrotactile reinforcement might be used, if shown effective in earlier experiments. All experimental events would thus be recorded along with brain/body imaging data from freely moving experiment participants to create a large database for studying relationships between operator attention-shifting and decision-making success, and model neurobehavioral differences between subjects.

B.2Addressing the lack of portable, user-acceptable (e.g., comfortably wearable), and robust systems for monitoring brain and body dynamics.

Portable high-density EEG systems are already available to study the EEG dynamics accompanying motivated actions in normal 3-D environments. However, a long-missing link between advancing the understanding of EEG signals and practical workplace applications has been the need to use wet gel to adhere EEG electrodes to the scalp and the need to bring scalp impedance of these contacts down to near 5 kΩ by abrading the scalp with a blunt needle or equivalent before each electrode application.

To enable high-quality EEG monitoring of naturally moving subjects, EEG systems must have characteristics not available in current brain imaging systems. To support dense spatial sampling, EEG sensors must be small and lightweight and not require special skin preparation. Further, the ideal system should avoid the risk of electrical bridging between nearby contacts by avoiding the use of conductive gel. To minimize weight and susceptibility to system movement artifacts, EEG acquisition and amplification circuits must also be small, lightweight, and battery-powered. To maximize mobility and allow near real-time use of the recorded data or measures derived from it, they may use wireless telemetry. Continuing research into microelectronic bio-sensors has led to several dry electrode designs (Alizadeh Taheri et al., 1996; Gondran et al., 1995; Griss et al., 2001), making truly mobile, wireless EEG systems incorporating dry sensor technology and small, lightweight, wearable data acquisition circuits now feasible and available for current experiments.

Our Alliance includes a team at NCTU, Taiwan (C-T Lin, lead), that is designing, building, and testing light, wearable, wireless, low-cost, high-density, microelectronic EEG systems with successively higher sensor densities. NCTU investigators, along with UCSD research partners, have recently demonstrated the feasibility of using dry microelectromechanical-system (MEMS) EEG sensors and miniaturized supporting hardware/software to continuously collect EEG data from four frontal non-hairy scalp sites in a realistic virtual-reality-based (VR) driving simulator (Lin et al., 2008) shown in figure 1. In the study of Lin et al. (2008), a signal-processing module was programmed to assess fluctuations in individuals' alertness and capacity for cognitive performance—accurate steering in a realistic driving simulator (left center)—based on EEG signals measured from the forehead by 4–8 dry electrodes embedded in the frontal brim of a baseball cap. The system also delivers arousing feedback to the driver (upper right) to maintain performance. This platform can be programmed to function in ways appropriate for other brain-system interface applications (Lin et al., 2008).

Figure 1. A wearable and wireless dry-electrode (WWD) EEG system that features dry MEMS EEG sensors (lower left), low-power signal acquisition, amplification and digitization, wireless telemetry (upper left), with online signal processing.

Despite such successes, more development and testing are needed to miniaturize the supporting hardware so as to collect high-density EEG data (64 channels or more) robustly and continuously from unconstrained, freely moving subjects in everyday environments. One of the biggest challenges to the current MEMS-based dry electrodes is the ability to acquire EEG signals from hairy scalp, as the current NCTU MEMS electrode is too short to "penetrate" the hair and make a good skin contact. The NCTU team has recently explored a potential remedy to this problem using a small dry electrode array with longer contact "fingers" (figure 2). The NCTU team is also developing a flexible electrode-supporting polymer substrate to construct the electrode "fingers." This electrode is constructed of metal embedded with polymer and coated by bio-friendly silver chloride (AgCl). Preliminary results have shown a strong correlation ($r > 0.92$) between the signals acquired by adjacent conventional wet and the new dry electrodes placed at adjacent scalp sites through the hair, indicating strong potential for the future development of EEG technologies that can support truly fieldable neuroergonomic systems designs.

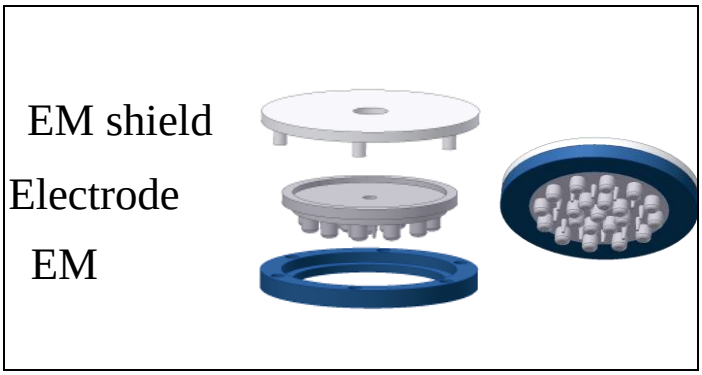

Figure 2. Through-the-hair dry electrode design. A yet newer (07/09), low-cost ($0.50U.S.) design (not shown) has "fingers" that make varying height and angle contacts with the scalp.

As with high-fidelity recording of brain activity, recording and analysis of body dynamics, eye movements, and physiological function is becoming progressively miniaturized for wearability. Methods for capturing unconstrained multi-joint motions of the head, limbs, and trunk in 3-D space have evolved rapidly over the last decades, engendering a paradigm shift in the field of motor control away from the study of simple movements such as single joint motions to the study of more complexly coordinated, multi-joint naturalistic movements. Positions of literally dozens of points on the limbs and body can now be captured with high spatial and temporal resolution. As well, lightweight, wearable eye tracking systems incorporating tiny microelectronic scene and eye cameras worn on an eyeglass frame are becoming available (http://www.arringtonresearch.com/scene.html).

B.3 Addressing the failure to record the whole of physical, mental, and physiological behavior that the brain controls in sufficient detail and across a sufficient breadth of circumstances.

The intent is to include and leverage information from such sources as overt motor behavior, eye movement, heart function (electrocardiography [ECG]), muscular activity (electromyogram [EMG]), and brain activity (EEG), as well as context cues regarding the multisensory task environment, in order to infer intentionality and examine the cognitive substrates on which motivated, goal-directed action is based. Only by combining these sources meaningfully can the information latent in the recorded brain/body/system dynamics be identified.

We believe that the study of motivated actions, performed within normal 3-D environments via combined high-density EEG, full-body motion capture, and eye tracking, essentially constitutes a new brain imaging modality, for which members of our Alliance team from the UCSD (S. Makeig, lead) have recently proposed the term "mobile brain/body imaging" (MoBI) (Makeig et al., 2009).

Within the CaN CTA program, MoBI data acquisition will include, but not be limited to, the following:

- *High-density EEG.* EEG is the only brain imaging modality with high temporal and fine (potentially cm^2-scale) spatial resolution that is lightweight enough to be worn in operational settings. Because of historical limitations in the size, weight, and cost of available high-density EEG systems, early brain-computer interface (BCI) systems have been designed to use a minimal number of recording channels. Recent advances in sensor and data acquisition design make mobile high-density EEG recording viable as a potential measurement modality. High-density, as opposed to low-density, EEG data are integral to the development of neuroergonomic systems as they provide a larger number of degrees of freedom, allowing much more flexibility in segregating brain EEG sources, within the *context of the advanced* data analytic and modeling approaches being developed within the CTA program.

- *Whole-body motion capture (mocap).* To interpret the function and meaning of brain EEG source signals, we need to know and understand *what processes these signals are actively supporting or controlling.* A most important part of this is physical behavior, yet heretofore little brain research has focused on the high-density brain dynamics supporting unrestricted physical activity—in particular, the distributed brain dynamics supporting *motivated, whole-body* action. Recent technical developments, however, allow recording of robust EEG signals from electrodes placed on the head surface in combination with detailed motion capture techniques. Understanding what aspects of the EEG relates to control of bodily actions allows better identification of those aspects of EEG source signals that index cognitive processes, including appraisal or evaluation of sensory events, and the motivation and intent of physical actions.

- *Wearable eye gaze tracking.* An aspect of behavior monitoring that is most important for understanding and monitoring cognitive processes involving visual perception is eye gaze and activity tracking. The human visual system processes both static and kinetic portions of the visual scene through a series of typically 3/s to 4/s saccadic jumps and fixations. The brain largely uses information gained during fixations to build and maintain 3-D visual awareness and direct active visual exploration of the environment, although the ways in which it does this are, so far, little understood.

The main CES experiment to be conducted at UCSD may involve an extended operational game space in which ally, foe, and indifferent agents will move and act. All experimental events will be recorded along with the MoBI data to create a large database for studying relationships between operator attention-shifting and decision-making success, and model neurobehavioral differences between subjects.

B.4Addressing the lack of mathematical modeling methods and software to find statistical relationships between moment-to-moment variations in environmental, behavioral, and functional brain dynamic recordings.

The planned research approach within the CaN CTA is one among many new scientific initiatives now becoming feasible because of accelerating advances in statistical or information-based signal processing and modeling. Many, if not all, of these new methods can be derived from Bayesian models of information contained in and conveyed by multidimensional data under various modeling assumptions. Statistics, once dominated by the need for simplifying (second-order Gaussian) assumptions required to retain closed-form analytic tractability, can now use much more data-adaptive and computationally-intensive statistical approaches. Such approaches allow automated discovery of joint higher-order structure in data. In particular, individual differences between subjects in an experiment no longer need to be treated as a cloud of Gaussian "noise." Nor do differences between experimental conditions need to be isolated by the experimental design and then separately tested in different conditions using orthogonal planned comparisons. Within the CaN CTA program, analytic approaches to characterizing and interpreting high-dimensional, MoBI data will include the following:

- *Information-based signal processing.* In particular, the independent component analysis (ICA), sparse Bayesian inverse, and new "context ICA" methods under development by UCSD Consortium members can allow automated discovery of relationships between brain dynamics and experimental contexts even in multimodal data from complex experiments. Further, individual subject differences revealed by the data can be subjected to the same discovery approach, thereby determining from the data themselves, rather than pre-supposing, the types and directions of relevant between-subjects differences. The CaN CTA program will build on these new methods, discovering the behavioral and brain dynamic patterns exhibited by individual operators in certain types of circumstances and then building multidimensional pattern recognition algorithms to monitor the appearance of these reactions during operationally relevant test sessions and, eventually, field operations.

- *Identifying Links Between Behavior and EEG Dynamics*. Interpreting the multimodal MoBI data described above requires development of adequate methods for modeling relationships between rapidly changing high-dimensional brain source activities and the complexities of natural motor behavior. To discover relationships between high-dimensional, synchronously recorded brain and body movement data, they first should be nonlinearly transformed in ways appropriate to the nature and origin of each type of data. Then, the structure of the transformed joint data may be explored using data-information-based machine learning methods (Baker et al., 2005) and EEG brain sources imaged using statistical inverse imaging methods (Michel et al., 2004; Wipf et al., 2007). Modeling transient coupling between activities of distributed, quasi-independent sources in different brain areas is a further important dimension of data mining and modeling research.

- *Multimodal Brain Imaging.* As MoBI technology and analysis methodologies are developed, investigations using a wide range of experimental paradigms will become possible, perhaps beginning with simple motivated actions such as 3-D orienting, pointing, and grasping (Hammon et al., 2008), and finally extending to a wide range of tasks and natural behaviors, including biomechanical adaptation and learning, navigation, and social interactions in real-world operational environments. Though many existing experimental designs in all these areas might be fruitfully exploited, the tight coupling between EEG, novelty, and appraisal of events suggests that these factors receive more explicit attention in MoBI experiment designs. The result of combining these sensor development, data analysis, and source imaging technologies should be the development, in coming years, of truly dynamic, higher-definition imaging of distributed EEG brain dynamics supporting natural cognition and behavior.

- *Exploitation of Graph Dynamics.* In the case of MoBI EEG real-time data capture, we will exploit our ability to extract distributed patterns (graphical constellations) of cortical dipole-patch activity using our ICA and sparse Bayesian learning (SBL) inverse problem solver, to determine appropriate graph invariants (see Ehrenfeucht, Harju, and Rozenberg, 1997; Graph Properties, n.d.). We will work with graph invariants (GI) appropriate for weighted as well as unweighted graphs, and will experimentally determine those GIs that are maximally robust to reasonably sized movements of EEG and body movement sensors and changes in EEG connectivity produced by sweat, grime, etc. A key intent of this approach is to greatly reduce the need for non-robust, baseline pre-calibration and tuning of the EEG sensors. We will also determine a list of GIs that encode independent information highly correlated with operator cognitive performance.

- *Hierarchical Bayesian Network Modeling.* Using either the raw time series of cortical dipole-patch activity data or times series of graph invariants, we will use both hierarchical Bayesian networks to obtain or further enhance higher-level features associated with cognitive and affective state. Such processing can also produce features that are robust to sensor and environmental degradation or be used to enhance the stability of GI features. At every level of the Bayes network, we will have a time series of abstracted state information will be used to estimate current, and predict future, operator state using the theory of Markov decision processes (MDP). For any given human operator, a MDP model can be refined to predict how that operator will respond in a specific situation. For example, it should be possible to determine if the operator is risk-preferring, risk-neutral, or risk-adverse. It may also be possible to predict how much stress an operator can sustain before he experiences a “fight-or-flight” reaction and which of the two alternatives the operator is more likely to engage in.

B.5 Addressing the lack of sufficient data archives and resources to systematically study relationships between individualized models derived for cognitive monitoring and individual differences in performance, cognitive ability, and personality, relationships that could optimize performance of cognitive monitoring systems while lowering requirements for collecting individual subject training data.

An important source of uncertainty here is the extent to which individualized brain/behavior models capable of accurately estimating Soldier cognitive state may require individualized model training data that may be prohibitively expensive to collect routinely, while having a prohibitive cost in model performance without such training data. A way out of this dilemma is to apply *collaborative filtering* principles (Han and Kamber, 2006) recently developed to use large data archives (including web archives and personal information archives) to build more accurate and complete models of individuals from fragmentary data by considering the totality of information available about other persons like the person of interest (e.g., in the same physical or categorical "neighborhood"). The CaN CTA will collect a database of brain/behavioral data from a sufficient number of subjects to allow exploration of the value of this approach for individualized cognitive monitoring in operational settings without requiring a prohibitive amount of personal training data to create models for new Soldier subjects.

Overarching Considerations for Addressing Scientific Barriers

Outlined above is a MoBI-based approach to addressing five scientific barriers to studying and precisely quantifying the natural interactions among Soldier brain, behavioral, sensory, and performance dynamics as situated within the operational environment. The successful implementation of such an approach must take into account several factors:

- *EEG sources*. Scalp EEG signals sum source activities arising within cortical domains whose local field activity becomes partially synchronized, giving rise to far-field potentials that each project, by volume conduction, to nearly all the scalp electrodes, where they are summed with differing strengths and polarities (Makeig et al., 2004a).

- *EEG and movements*. It seems likely that the brain may use naturally emergent local field synchronies (cortical EEG sources) to focus its extremely high-dimensional synaptic scale activity onto much lower-dimensional control of motor behavior. If so, then regular relationships between EEG and motor actions may be found in MoBI data. Particularly salient relationships between EEG and body movements may occur at movement decision points, especially pronounced when movements are distinctly motivated, for example, quick reactions to threatening events.

- *Loci of expected effects.* Many cortical regions are interactively involved in supporting motivated motor behavior—not only primary motor areas directly supporting brain motor commands, but also areas supporting motor planning and expectation, perceptual motor and sensorimotor integration, and spatial awareness and executive function, including areas

directly connected to sub-cortical brain "valuation" systems that support rapid behavioral adjustments to anticipated or potential threats, rewards, and errors.

- *Correlation versus causation*. Observed relationships between EEG changes and motor actions may not always reflect a direct neural coupling. For example, continual changes in the cortical distribution of alpha band power during inquisitive movements may index concurrent shifts in the distribution of sensory attention (Worden et al., 2000) rather than or in addition to motor planning or execution processes.
- *EEG artifacts*. A primary challenge to performing EEG brain imaging in mobile circumstances is extracting meaningful event-related brain dynamics from signals that necessarily include significant non-brain artifacts arising from subject eye movements, head and neck EMG activity, cardiac artifacts, line noise, and other non-brain sources. A signal processing approach developed over the last two decades, ICA (Bell and Sejnowski, 1995) has proven to be effective for EEG decomposition into functionally and physiologically distinct source activities (Makeig and Jung, 1996; Makeig et al., 2002).

ICA decomposition is a data-driven method that results in a set of spatial filters, each of which passes information from a distinct information source in the recorded multichannel data (Makeig et al., 2004a). In particular, ICA can be an effective method of identifying and separating several classes of artifacts (Jung et al., 2000). Under favorable circumstances, ICA decomposition of continuous or discontinuous high-density EEG data also allows the separate and concurrent monitoring of dozens of EEG brain as well as non-brain artifact sources, thus avoiding much of the often severe data reduction integral to traditional methods that reject from analysis EEG data epochs containing movement artifacts.

Applied to data from mobile participants, ICA can separate and monitor EMG activity from individual head and neck muscles that, since they do not move appreciably and have spatially fixed patterns of projection to the EEG electrodes. ICA can also isolate into a small subspace other artifacts whose projections to the recording array are not static but move in spatially stereotyped patterns, for example, slow blinks or cardiac artifacts. Spatially labile, non-stereotyped artifacts, however, can quickly spew hundreds of unique scalp distributions into the data, each *de facto* independent of the rest of the recorded data and not separable into a low-dimensional independent component (IC) subspace. For example, such artifacts may result if extreme head and scalp movements produce small movements of many of the electrodes on the scalp. Such spatially non-stereotyped artifacts need to be identified and removed from the training data before or during ICA decomposition (Onton et al., 2006).

- *Brain data preprocessing*. Scalp-recorded EEG signals are each mixtures of activity from a variety of brain as well as non-brain sources, and the number of possible brain source domains (e.g., cortical patches) is quite large. Thus, the problem of identifying the unknown EEG source signals and their individual projections to the scalp sensors from the data is a difficult blind source separation and physical inverse problem. Methods and

software for imaging the source dynamics of cortical activity from high-density scalp recordings are steadily evolving (Michel et al., 2004). Applied to EEG data, ICA algorithms result in a set of spatial filters that linearly separate EEG into a sum of component processes with maximally temporally independent time courses (Makeig et al., 1996; Makeig et al., 2004a; Makeig et al., 2004b).

Many IC source processes project to the scalp with a nearly "dipolar" pattern compatible with a cortical patch source. Spatial equivalent dipole location (in or near brain, in or near eyes, or scalp muscles) can be estimated using an electrical head model, optimally one built from the participant MR head image (Mosher et al., 1999). Open source software is available (Delorme and Makeig, 2004), and use of anatomic magnetic resonance (MR) subject head images can produce the most accurate source location estimates (Akalin, Acar and Makeig, 2010). However, from the point of view of dynamic analysis, ICA decomposition into separate source activities can also be considered a signal pre-processing step to enable further joint analysis of the brain EEG and behavioral data.

- *Movement data preprocessing*. Pre-processing of body motion capture data is likewise non-trivial. Modern biomechanical data analysis proceeds from recording the changing positions, velocities, and/or accelerations, in external world or body-centered coordinates, of sensors placed on the body surface, to computing movements of each body and limb segment relative to another in a body-centered reference frame, to estimating the time courses of the particular muscular forces that produce those joint movements (Poizner et al., 1995; Soechting and Flanders, 1995). Determining joint movements from motion capture records is a mathematical inverse problem, as a kinematic transformation is needed between trajectories of the recorded body surface positions and those of the underlying joint angles (Soechting and Flanders, 1992). Determining the muscular torques applied to the limb segments to produce the observed joint/limb trajectories is a further inverse problem requiring a biomechanical model of the body skeleton and musculature (Winter and Eng, 1995), for which open source software is becoming available (Delp et al., 2007). It is not clear, however, the extent to which EEG changes relate more directly to changes in body or body-part position, movement, or muscular activation—or to some combination of these. This uncertainty complicates the development of mobile brain/body imaging models of human action.

3.2 Translational Science Within Specific Neurocognitive Performance Domains

As stated before, our research program targets operations in complex, mixed-initiative system environments in which dynamic, complex information streams must be integrated across multiple spatial and temporal scales. To address this target, the research much address three main objectives as preconditions on solving these problems: help the Soldier-system (1) *actively maintain situational awareness* of the immediate and larger-scale operational environment based on ever-changing information delivered concurrently via multiple sensory channels (i.e.,

visual,auditory, tactile); (2) *make sound decisions and develop appropriate courses of action* in response to unfolding events in their environment, through improved understanding of sensory and cognitive processing achieved by combining real-time analysis of operator brain activity, body and eye movements, and behavior, with information gleaned from analysis of the sensory streams the operators are monitoring; and (3) *take into account inter- and intra-individual variability* in the neurocognitive and behavioral strengths and strategies of operators to optimize Soldier-system information exchange to improve the likelihood of success associated with making risky decisions.

While the previous section outlined a MoBI-based approach to overcoming the barriers to understanding brain-behavior-environment interdependencies, this section outlines the neurocognitive performance domains in which the CaN CTA research focuses on in order to accomplish our main objectives and translate basic neuroscience to militarily relevant environments. The performance domains include the following:

- ***Alertness***. In low or constant information settings, frank drowsiness and even sleep onset may accompany intentions to remain alert and attentive. Jung et al. (1997) showed that human EEG contains abundant and stable information sufficient to alert a computerized system that its human operator is drowsy or somnolent—information that is still not integrated into human-system interface designs—though in a wide range of settings, contra-circadian demands on operator time and attention continue to increase, with statistically probable and likely under-appreciated consequences for overall human-system performance including increased risk of disasters produced by human performance failure ("man out of the loop").
- ***Attention***. We are likely little aware of the extent to which we are continually redistributing our attention among sensory, mnemonic, and cognitive channels. Failure to properly scan the environment for crucial information is a hallmark of performance under stress. Even physically scanning across visual information sources with our eyes does not, however, guarantee that we effectively attend to significant visual information within our field of view. For example, we may be at the time primarily focusing on receiving and evaluating audio information, or we may be daydreaming about a pleasant memory or anticipated event. More research is needed to determine to what extent the depth, distribution, and dynamics of attention may be modeled and accurately estimated from MoBI data. A phenomenon to exploit is the known appearance of alpha band (8–12 Hz) EEG activity in cortical regions used to monitor relatively unattended sensory channels (Gomez-Ramirez et al., 2011; Kelly et al., 2006).
- ***Arousal***. The relationship between performance and arousal has long been known to assume a well-known inverted U shape, with both under-aroused and over-aroused interest and attentiveness dissociated from good performance. Under-arousal leads to failure to explore the sensory environment and recognize consequences of stimulus or event

combinations, while over-arousal leads to "tunnel vision" fixation on a particular fact or input or even an inability to focus on external inputs at all. Likely phenomenon to exploit here is the appearance of coherent beta band (14–28 Hz) EEG activities in sensory cortex during aroused attention (Bekisz and Wróbel, 1993).

- ***Appraisal***. Understanding the cognitive significance of operator EEG, eye movement, and other behavioral processes logically requires knowledge and understanding of the sensory experience of the operator. This is perhaps the most challenging of the inverse problems involved in the development of neuroergonomic systems, as robust computer interpretation of the significance of complex natural sensory information (visual, auditory, etc.) is not yet within reach. However, interpretation of EEG signals recorded during shifting of attention between any combination of sensory channels may be aided by even partial information, e.g., about the degree of predictability of stimulus events that may be gleaned from the sensory stimuli themselves.

Recent work in computational linguistics has shown that statistically defined linguistic surprisal (the inverse of sequential word probability) can determine the length of individual fixations during text reading, and direct relations between linguistic surprisal and EEG are now well established. In addition, automated speech to text translation is now relatively advanced, as is automatic grammatical parsing from text. More basic research is needed, however, in EEG dynamics accompanying speech listening and text reading. Understanding which aspects of the EEG signal are related to what is heard (or read) will help to isolate those signal aspects that index an operator's ("top-down") appraisal of the speech content.

Recent work in machine vision has shown the possibility of defining screen regions of bottom-up visual interest in video images via statistical definitions of visual surprise, and these have been shown to well predict locations of eye fixation. Basic research is needed to better understand which aspects of EEG, psychophysiological, and behavioral signals relate to top-down visual search versus responses to events of bottom-up visual interest, and interpret visual information acquired during individual eye fixations.

A potentially valuable capability for MoBI-enabled human system interface designs is the capacity to detect self-perceived or unperceived failures to appraise the significance of sensory events or event combinations. A simple case might be failure of brain activity or body movements to register an alerting reaction to delivery of a signal to the operator known to require urgent evaluation (e.g., a "red warning light"). A more complex example would be the capacity to detect confusion in an operator presented with confusing, incomplete, and/or contradictory information.

- ***Affect***. Recent EEG analysis has begun to show that our emotional or affectively laden brain responses to events that our brain's limbic system immediately characterizes as "good" or potentially "bad" news can be discerned from high-density EEG data (Onton and Makeig, 2009). We are quite sensitive to teammates' affective characterization of events,

as well—a co-worker's sudden intake of breath may immediately arouse us to shift our attention to find the cause of their affectively laden response. Recent demonstrations have shown that automated recognition of unexpected negative events (for example, sudden failures of a computer game program to follow operator instructions) can be automatically detected from scalp EEG signals and may be used in a human-computer interface to improve overall human-system performance. Rapid fluctuations in brain "good/bad" responses to events, if made known to a computer information system an operator is controlling, could be used to selectively change display patterns, for example, while the absence of an affectively laden brain response to an event the system knows to be important (e.g., "Warning light on!") could cue further useful system actions. Detection and representation of the unexpected abnormal mood of an out-of-sight team member might foster better team cohesiveness and performance. Brain affective responses of expert observers (including mental "Oh no!'s") might also be used to give more effective, near-instant and continuous feedback to robotic systems that are being trained to perform through experience than manual expert feedback delivery methods.

- ***Agency***. Recent work has shown that intention to make a voluntary movement to the left or right produces distinct and recognizable patterns of electrical activity on the parietal scalp, consistent with locations of spatial planning areas found in invasive animal and human fMRI brain studies (Wang and Makeig, 2009). An information display system that can anticipate the motivated actions of its operator(s) might be designed to be easier and more efficient to operate than a passive system with no knowledge of operator intent.

Cognitive and affective aspects of operator intent in making an action may also be crucial in optimizing system response. For example, might a system detect the fact that an operator perceives he/she has pressed a button in error, then give the operator an opportunity to confirm or rescind the command? Else, by interpreting the speed of a motor selection gesture plus accompanying brain dynamics consistent with perceived urgency, might a system be able to usefully refocus its information delivery capabilities to maximize delivery of relevant information and feedback, as a human colleague might do?

4. Transitions

Over the course of the CaN CTA, the Alliance will perform translational research that builds on the information gained through basic research and is envisioned to result in practical solutions that address particular Army problems or unmet needs. Potential endpoints of the envisioned research are both products that ultimately are integrated into Army systems and new pathways to discovery, which would include new methods of investigation; new approaches for summarizing, visualizing, and analyzing data; new measures or biological markers for detecting specific

cognitive states or processes such as fatigue, attention allocation, working memory, stress, learning, etc.; and new algorithms for differentiating among such states.

This section outlines three planned transition efforts (TEs) to which the research projects can contribute. These TEs can thus serve as guideposts for investigators as they plan and execute respective projects. The three projects identified were designed to be somewhat progressive in nature. That is, as a close examination of the included timelines will reveal, the accomplishments of TE I will feed the objectives and goals underlying the advancement of TE II and so on.

Described below are the three TEs, followed by descriptions of their background, potential barriers, timelines, and specific transitions. Additionally, a corresponding Translational Path section is provided within the description of each individual research project in sections 4, 5, and 6 that explains the connection between each project and these TEs. The three initial planned, progressive TEs for the basic research conducted under the CaN CTA are as follows:

TE I. MoBI methods for detecting changes in vehicle operator alertness and consequent performance-failure prediction (near-term transition to Army systems)

TE II. Advanced tools for MoBI-based neurocognitive performance assessment (Integrated Army and Research transition; near- and mid-term transition to research tools; mid- and far-term transition to Army systems)

TE III. Enhanced design of high-information multichannel crew stations (far-term Army transition, 5 years)

Additional potential transitions, outside of these pre-defined TEs, will be identified as appropriate (e.g., opportunity-driven transitions will be developed and described over the course of the CTA).

4.1 TE I: MoBI for Detecting Changes in Vehicle Operator Alertness and Performance Prediction

A consistent and critical problem for Soldiers lays in maintaining alertness and vigilance while performing attention-demanding, long-duration tasks such as driving within dynamic, threat-laden environments. This near-term TE integrates basic science and technology into a mobile/wireless cognitive-state monitoring system that can assess fluctuations in individuals' alertness and capacity for driving performance via low-density EEG signals. We aim to integrate and demonstrate such a monitor into a military vehicle test-bed.

4.1.1 TE I. Background

Since 1989, Alliance team members at UCSD have conducted fundamental studies (Makeig and Inlow, 1993; Makeig and Jung, 1995, 1996; Jung et al., 1997; Makeig et al., 2000) demonstrating the feasibility of accurately estimating shifts in an individual operator's level of alertness, as

indexed by changes in their level of performance on a simple auditory target detection task, by monitoring the changes in their EEG power spectra or other measures. Recently, NCTU investigator Lin and UCSD investigator Jung have extended this research into EEG-based alertness assessment in a continuous driving task (Lin et al., 2005, 2006).

Alliance team members have also conducted basic research underlying cutting-edge technologies for the real-time joint recording and analysis of environmental, behavioral, and functional brain dynamic variables. For example, team members at NCTU and UCSD have recently demonstrated the feasibility of using dry MEMS EEG sensors and miniaturized supporting hardware/software to continuously collect EEG data from four frontal non-hairy scalp sites in a realistic VR-based driving simulator (Lin et al. 2008).

This TE will integrate results from over a decade of research in Alliance partner laboratories related to the Neurocognitive Performance TA and the Neurotechnology TA, providing a real-time Soldier monitoring system that can be implemented into a military vehicle test-bed. Further, this transition effort will provide a near-term demonstration of the translational process that can serve as a guide for the successful transition of future CaN CTA research products.

4.1.2 TE I. Transition Barriers and Hurdles

Previous research has suggested that an operator alertness/performance-failure prediction monitor for in-vehicle driving may be sufficiently robust to be accomplished without fully addressing scientific barriers B.3–5, though we expect their reliability to further increase as barriers B.3–5 are addressed. This is one of the primary reasons that this effort was selected as the first TE, and as a near-term demonstration of the translational process. The primary scientific barriers that this effort will address are as follows.

B.1 The restriction of experimental designs to highly controlled and impoverished stimulus/response paradigms and environments.

The monitor must be robust against a variety of subject states, task conditions, and environmental scenarios that are expected in real-world situations.

B.2 The lack of portable, user-acceptable (e.g., comfortably wearable), and robust systems for monitoring brain and body dynamics.

The monitor needs to able to use *reasonably low-density* EEG data robustly and continuously without the use of conductive gels or skin preparation from harnessed, seated operators that are also free to dismount their vehicles. Available dry EEG sensor density is expected to increase rapidly in coming years, and the value of spatial filtering possibilities afforded by higher-density recording, for accuracy in both non-brain artifact rejection and relevant brain source monitoring, has been well established (e.g., Makeig et al., 2004a). However, previous results (e.g., Jung et al., 1997) suggest that individualized or even common low-density EEG-based models can

provide accurate continuous alertness estimates, at least in laboratory settings including use of simulated vehicle movements (Lin et al., 2008).

B.5 The lack of sufficient data archives and resources to systematically study relationships between individualized models derived for cognitive monitoring and individual differences in performance, cognitive ability, and personality, relationships that could optimize performance of cognitive monitoring systems while lowering requirements for collecting individual subject training data.

The monitor should be able to use a model of brain/behavioral changes in alertness not requiring extensive pilot training data from each Soldier, while respecting operator differences in, e.g., baseline EEG that may be present in recordings from each new Soldier subject. Applied studies under TE I using a number of subjects will allow early investigation within the CTA of the extent to which individualized data models perform better than a common data model, while computational approaches to characterizing relationships between individual and group data, developed under B.5 will allow first testing of methods to quickly individualize a common model from partial (baseline) EEG data on each individual.

In addition to the scientific barriers, the translational process will have to address technical challenges. This primary technical challenge that the operator alertness/performance prediction monitor will face is as follows:

- The monitor must be compatible with integration into current Army equipment in a manner that is physically robust, safe, and acceptable to the user.

4.1.3 TE I. Translational Timeline

The areas underlying this transition are threefold. First, we will develop and test a wearable, wireless, dry-electrode, low-density, EEG-based system that can be used in field-able scenarios. This system will be capable of data acquisition, online artifact cancellation and signal processing. Second, we will develop and validate robust EEG algorithms for monitoring alertness and cognitive performance estimation in militarily relevant environments. Third, we will integrate a ruggedized, wearable, EEG-based system into a helmet suitable for experimentation in a military vehicle test-bed. The planned transition of this ruggedized, wearable EEG-based monitor will be to an Army applied research and development program that will implement this monitor into adaptive brain-machine interfaces. This timeline is depicted in figure 3.

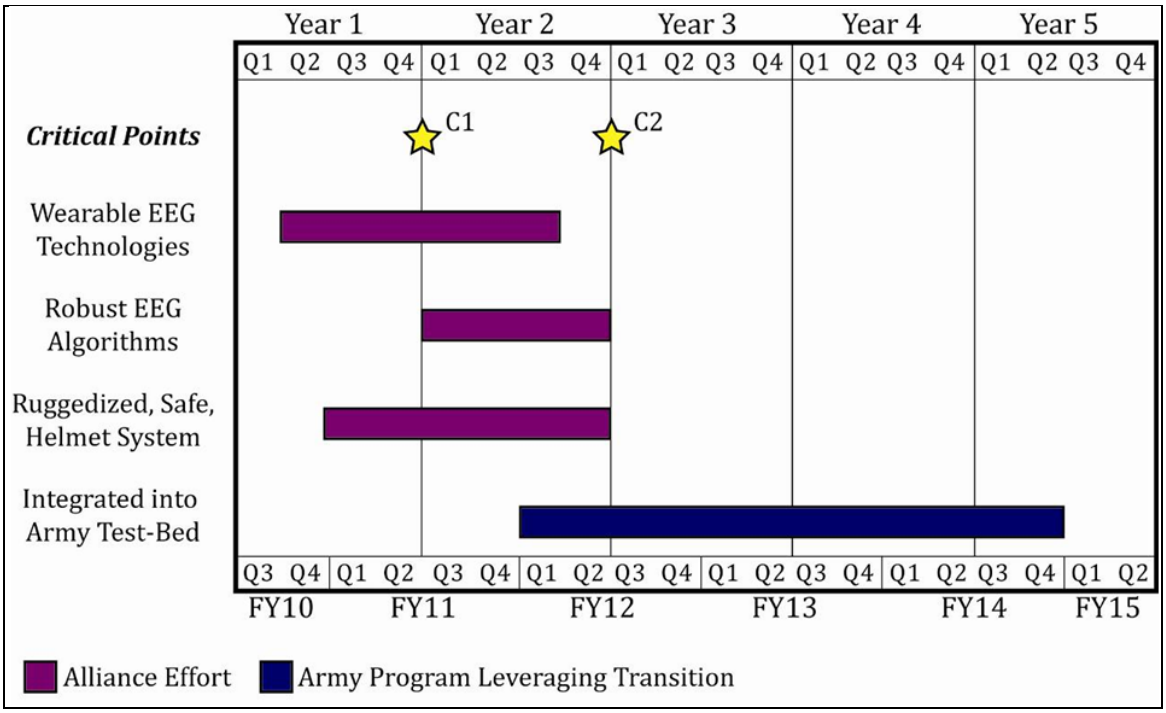

Figure 3. Translational timeline depicting expected progress in TE I.

In Year 1, the Alliance translational research projects for this TE will support the development and evaluation of a new 16-channel mobile and wireless EEG system to acquire signals from all parts of the scalp. In year 2, the Alliance will (1) test the long-term signal quality of EEG signals in tasks involving a wide range of events requiring active evaluation by operators in the real-world environments, and (2) develop, test, and demonstrate a wearable/wireless alertness monitoring and management system. These efforts are described in the Alliance research projects supporting this transition, which include the following:

- MoBI-based Feedback for Training Automated Systems and System Operators (MBF)
- Operator Dynamics of Event Appraisal (ODE)
- Using Neural Activity to Predict Attentional Lapses During Multisensory Task Scenarios (PAL)
- Effects of Vehicle Motion and Cognitive Fatigue (VMF)
- Wearable EEG Development and Testing (WDT)

In addition to the research projects, this transition will require specific efforts to address the following technical challenges:

- Through years 1 and 2 ARL will lead an effort with UCSD to integrate Alliance developed sensors within a standard Army helmet for testing of feasibility and potential safety concerns. This effort (lead, Dave Kuhn) will include examining the feasibility of integrating several sensor and data acquisition options and finally constructing a prototype in-helmet system.

Critical Points

There are two critical points for the successful completion of this project.

C.1. The specifics of the wearable EEG-sensor system will be agreed upon.

C.2. The monitor will be transitioned to the applied Army research program.

4.1.4 TE I. Transitions

This TE will culminate with the integration and demonstration of a mobile/wireless cognitive-state monitoring system that can assess fluctuations in individuals' alertness and capacity for driving performance via low-density EEG signals in a military vehicle test-bed. Through a joint U.S. Army Tank-Automotive Research Development and Engineering Center (TARDEC)-ARL mission program, the alertness/performance monitoring system will be integrated into three types of applications: (1) an individual-based fatigue mitigation system, (2) a team-based warning system, and (3) an adaptive training system. The mitigation and warning systems will be designed to enhance Soldier-system performance for driving tasks. The training system will be designed to reduce training time.

The longer-term significance of the TE includes (1) demonstrating a viable prototype in-helmet system for high quality EEG capture and evaluation in a wide range of military relevant environments; (2) enabling safe and secure EEG-based monitoring in operational tests to include use in system development, test and evaluation, and (potentially) in the field; and (3) providing a proof of principle for other types of cognitive-state monitoring and alternative uses such as in a traumatic brain injury (TBI) detection or monitoring system. In addition, by enabling recording of brain dynamics in more complex operational environments than is currently possible, there will be broader implications for later transitions in other areas for all of the research supporting the near-term development of a mobile/wireless cognitive-state monitoring system that can assess fluctuations in individuals' alertness.

For example, having a capability to safely and reliably record brain dynamics of Soldiers in operational environments will enable future investigations of Soldier neurocognitive function in more diverse operational environments (relating to TA I). In like fashion, transitions from other TEs will contribute to further enhance the alertness technology. For example, developing the capability to integrate and synchronize multiple streams of data will enable integration of additional contextual data that could improve the accuracy of estimating operator alertness just as the further development of data analysis and mining tools and techniques (TA II) may lead to

other applications for brain monitoring beyond just fatigue (e.g., detecting shifts in attention, cognitive load, and TBI).

4.2 TE II. Advanced Tools for MoBI and Neurocognitive Performance Assessment

A critical need for translation of neuroscience to operational environments is the appropriate hardware and software tools for collecting, analyzing, interpreting, and using brain imaging data within real-world environments. This planned TE provides tools that will enable more advanced monitoring of Soldier performance in operational environments as the research evolves from laboratory to simulation to real-world environments. Specifically, this transition effort focuses on the development of (1) sensor technologies and mobile recording systems; (2) large-scale databases; (3) hardware and software for integrating and synchronizing multiple data streams and data formats; and (4) algorithms for mining, analyzing and visualizing data for investigating relations among multivariate data sets comprised of data spanning different temporal and spatial scales and formats. Two primary types of transitions will occur from this effort: first, in the near and intermediate term, user-friendly research tools will be implemented that are necessary for the Department of Defense (DoD) translational neuroscience community and the scientific community at large; and second, in the intermediate to long-term, real-time tools will be implemented that enable advanced Soldier monitoring and brain-in-the-loop system design.

4.2.1 TE II. Background

Alliance partners at, UCSD, NCTU, UTSA, DCS Corporation, and ARL have a long history of developing hardware and software tools for collection, visualization, analysis, and interpretation of data ranging from basic neuroscience to Soldier-system performance. For example, partners at UCSD have a 13-year history in developing an interactive, freely available Matlab toolbox for processing continuous and event-related electrophysiological data (Delorme and Makeig, 2004; Makeig, Debener, Onton and Delorme, 2004; Swartz Center for Computational Neuroscience, n.d.). In a long-term collaborative effort, partners at UCSD and NCTU have developed tools for data collection, analysis, and interpretation of EEG data in a limited-range of real-world settings. Similarly, an Alliance partner at UTSA has developed tools for visualization, analysis, and management of multimedia datasets in three major application areas: biological applications (in neuroscience, immunology, and bioinformatics), pattern forming systems, and geophysical systems (Robbins, Robinson and Senseman, 2004; Robbins, Grinshpan, Allen and Senseman, 2004; Robbins and Senseman, 2003; UTSA Visualization and Modeling Laboratory, n.d.). In another long-term collaboration, partners at DCS Corp and ARL have developed tools for the modeling and simulation (Johnson, Manteuffel, Brewster and Tierney, 2007) as well as the collection and analysis (Metcalfe et al, 2010) of data regarding human-system performance in militarily relevant tasks and contexts. Beyond software development, in efforts that are becoming integrated with neuroergonomics research (Oie and Paul, 2009), ARL and DCS have long worked collaboratively with the U.S. Army TARDEC to develop paradigms and techniques for assessing performance in real-world tasks that use high-fidelity vehicle simulations using a

6-degrees of freedom (DOF) motion simulator (McDowell, Rider, Truong, and Paul, 2005; Ruffner et al., 2005). This TE will leverage the wide-ranging expertise of Alliance partners to integrate research from the Neurocognitive Performance TA, the Advanced Computational Methods TA, and the Neurotechnology TA research strands to provide advanced tools that will serve as critical capabilities for applied researchers and as foundational capabilities upon which future technologies will build.

4.2.2 TE II. Transition Barriers and Hurdles

While a large variety of advanced imaging and computational tools and techniques have been developed and successfully employed within the neuroscientific community, the vast majority of the technologies used have been limited to laboratory, fixed-environment contexts for the purpose of offline processing and analysis of neurobehavioral function. Thus, further work is needed towards developing analysis approaches that provide insight into neurobehavioral function as humans continuously interact with dynamic, high-information content environments. There has been little appreciation of the problems encountered when assessing neurocognitive performance in real-time within real, dynamic environments. Neither has much attention been given to the particular challenges associated with the real-time application of multiple sensor technologies for joint analysis of several typically high-density sources of information regarding brain and behavioral dynamics. This tool development TE, therefore, will have to address all five primary scientific barriers.

B.1 The restriction of experimental designs to highly controlled and impoverished stimulus/response paradigms and environments.

Tools must advance beyond those developed for highly controlled and impoverished scenarios. Tools developed under traditional paradigms may not be robust enough for application in highly complex environments or multi-tasking scenarios, or for operation in multiple or fluctuating performance domains.

B.2 The lack of portable, user-acceptable (e.g., comfortably wearable), and robust systems for monitoring brain and body dynamics.

Multi-purpose acquisition systems need to able to collect high-fidelity EEG data robustly and continuously without the use of conductive gels or skin preparation. Further, portable systems must robustly handle electrical and motion artifacts that pose threats to reliable and valid recording of brain dynamics in operational environments.

B.3 The failure to record the whole of physical, mental, and physiological behavior that the brain controls, and the physical and socio-cultural effects of the environment that impact brain function, in sufficient detail and across a sufficient breadth of circumstances.

Data acquisition systems must be generic or adaptable enough to collect data in the sufficient detail and across a breadth of circumstances. Such systems must incorporate a wide-range of

sensor technologies and thus must address issues associated with sampling rate, synchronization, data storage, and subsequent data retrieval. Specifically, multi-aspect datasets collecting high-density data from differing types of physiological sources (e.g., EEG, EMG, eye and body movements) are often very large and unwieldy in raw form.

B.4 The lack of mathematical modeling methods and software to find statistical relationships between moment-to-moment variations in environmental, behavioral, and functional brain dynamic recordings.

Due to the novelty and the scale of the large, multi-aspect datasets expected from within operationally relevant scenarios, new tools for data-reduction, mining, and visualization must be developed. In particular, as systems progress towards real-time implementations, such tools must enable developers to constrain system designs to utilize only the necessary and sufficient data as opposed to online mining and processing of overwhelming amounts of data.

B.5 The lack of sufficient data archives and resources to systematically study relationships between individualized models derived for cognitive monitoring and individual differences in performance, cognitive ability, and personality, relationships that could optimize performance of cognitive monitoring systems while lowering requirements for collecting individual subject training data.

The tools designed and tested under TE II should enable the use of models of brain/behavioral changes not requiring extensive pilot training data from each Soldier, while respecting operator differences in, e.g., baseline EEG that may be present in recordings from each new Soldier subject. Applied studies under TE II using a number of subjects will allow early investigation within the CTA of the extent to which individualized data models perform better than a common data model, while computational approaches to characterizing relationships between individual and group data, developed under B.5 will allow first testing of methods to quickly individualize a common model from partial (baseline) EEG data on each individual.

In addition to the scientific barriers, the translational process will have to address technical challenges. The primary technical challenges that the advanced tools for brain imaging and neurocognitive evaluation TE will face are as follows:

- Research tools must be understandable, robust, and usable by personnel with basic entry-level programming and research skills.
- High-density EEG collection system must be compatible with integration into current Army equipment in a manner that is both physically robust and safe for the user.
- Real-time tools must be optimized for speed and allow system developers the flexibility to integrate with a variety of system configurations.

4.2.3 TE II. Transitional Timeline

Six primary Alliance research topic areas feed into this TE:

1. We will develop hardware and software tools to collect, synchronize, and organize multiple data streams and formats, empowering us to observe and record a variety of levels (physiological, physical, and environmental) of neurobehavioral data regarding operator and environmental state.

2. We will refine and validate acquisition hardware and related tools for use in complex operational environments.

3. The Alliance will develop, refine, and validate software tools and algorithms for the visualization, mining, and analysis of the complex, high-density data streams to be obtained through CTA efforts. This effort is a most critical link in the proposed research, since combining brain, body, and performance measures to create cognitive monitoring models is both highly innovative and has never been attempted before, thus requiring a strong and continued focus of expertise and effort by several CaN CTA computational investigators working in concert with CaN CTA experimental researchers.

4. The acquisition, reduction, and mining tools will be assessed and tuned for usability and robust application across experimental tasks and in a variety of experimental contexts.

5. Accompanying and following the tool development, a fifth area for this TE will explore and apply data acquisition, reduction, and mining tools and techniques to real-time systems. This, again, is a critical link that will require strong innovation and continued collaboration among computational and experimental CaN CTA researchers.

6. The hardware and software developed for implementation in real-time systems will be assessed and further matured for enhanced usability and ruggedized for implementation in Army test-bed systems.

As shown in figure 4, there will be two main transitions that result from efforts in the six focus areas. Once available, the software and hardware tools developed in the first four focus areas will be leveraged into DoD programs (outside of the Alliance collaborators) that aim to study and use information regarding Soldier neurocognitive performance and the brain/behavioral dynamics supporting it. Likewise, as the system is translated into a set of robust tools and methods for real-time use through efforts in the fifth and sixth focus areas, the Alliance will collaborate to facilitate the integration of the neurotechnologies within Army test-beds.

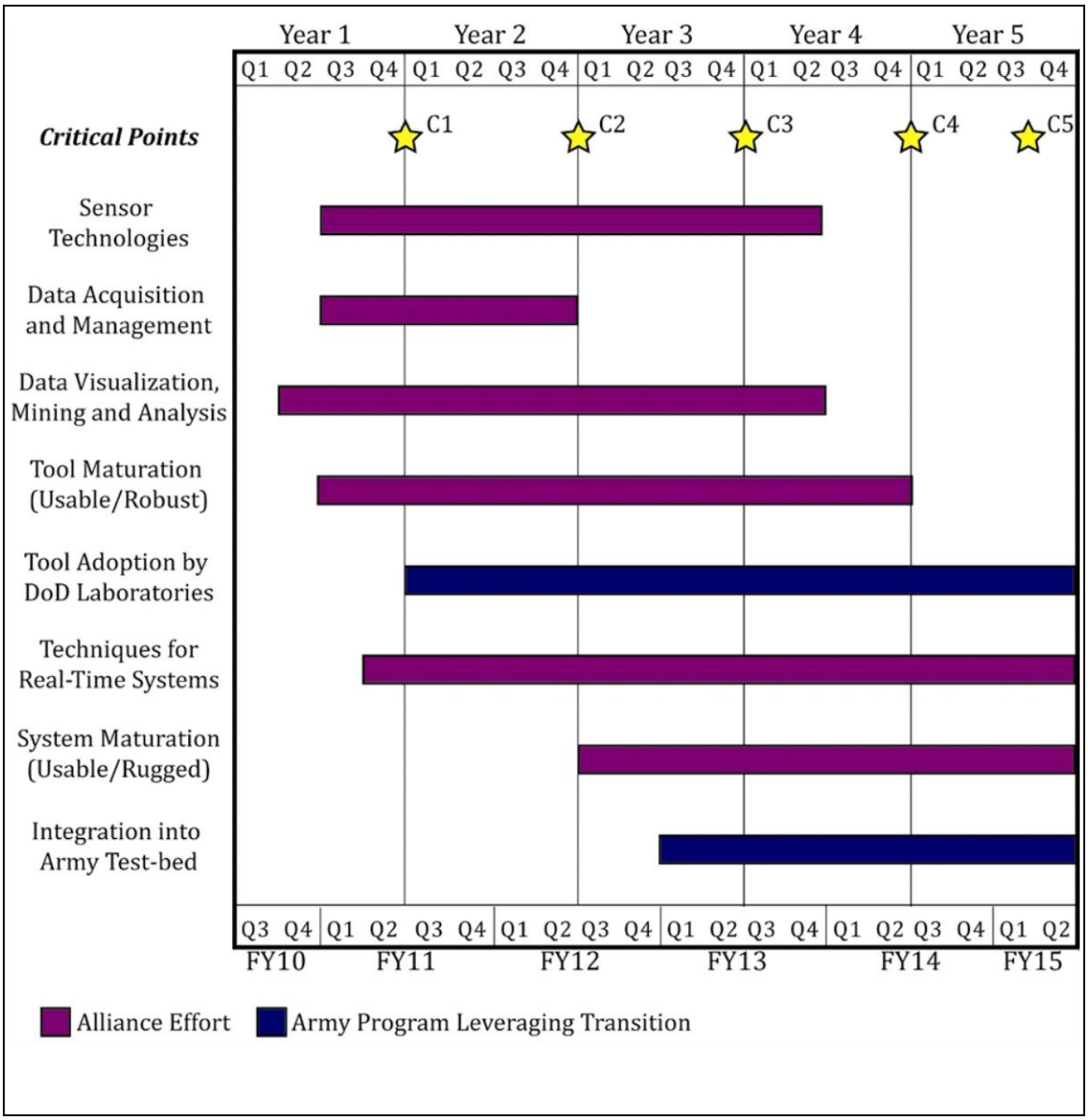

Figure 4. Translational timeline depicting expected progress in TE II.

Advanced tools will be continually developed, refined, and matured throughout the duration of the CTA program. In the first year, efforts will be focused on primarily in three key areas: (1) the development of hardware and software supporting acquisition of high-density data regarding neurocognitive performance, (2) the development of a central database structure and format for archiving data from all CTA research, and (3) large-scale data mining (enable by area 2) beginning in the first year and continuing over subsequent years as data are generated and integrated into the database. Developing a central database will require parallel development of a cyber infrastructure for integrating joint brain, behavior, and environmental data and analyzing multi-factorial datasets using high-performance computing. We will also develop an experimental real-time interactive control and analysis (ERICA) system with UCSD's DataRiver

system (Vankov et al., 2010) for distributed data acquisition, synchronization, online processing, and stimulus delivery in the first year. Initial efforts in the first year will also focus on preliminary real-time analysis techniques and tool maturation for existing toolboxes.

From year 2 onward, the acquisition, reduction, and mining tools developed will be applied, assessed, and refined for greater integration of highly multivariate, multi-aspect neurobehavioral data as well as later progress towards application in real-time systems. As shown in the timeline in figure 4, much of the development for this TE will proceed in parallel, with data acquisition feeding, for example, mining and visualization tools that will likewise, feed information back for refinement of the hardware and software tools underlying the data acquisition process itself, as well as experimental design features that may be required to test and extend them.

Similarly, the maturation of the tools for usability and robustness across tasks and contexts will enable their adoption for use by other DoD laboratories that, in turn, may provide feedback and suggestions for subsequent tool refinement and maturation. Research in from the third year onward focuses on exploiting and extending the developments from the first two years and exploiting the technologies from TE I, as well as on the maturation and ruggedization of systems for use in real-world settings.

These efforts are described in the Alliance research projects supporting this transition, which include the following:

- Brain Dynamics of Attention Shifting (DAS)
- Experimental Real-time Control (ERC)
- Data Fusion, Summary, and Visualization (FSV)
- MBF
- Multi-Screen Search (MSS)
- Neurocomputation (NCP)
- Speech Comprehension and Neurolinguistics (SCN)
- VMF
- WDT

In addition to the research projects, this TE will require additional specific efforts to address the technical challenges.

- Through all years, as tools approach completion, ARL will lead an effort, in collaboration with DCS Corp, to evaluate developed algorithms, interfaces, and hardware for general usability and appropriateness for research laboratory and in-field use. In the initial two

years, this effort (lead Chris Stachowiak) will focus on the usability and general human factors of Matlab-based software tools developed.

Critical Points

There are five critical points in the successful completion of this project:

C.1. The required specifications for the data acquisition hardware, software, and file formats will be defined and agreed upon. Usability standards for software tools will be described and defined. The ERICA software system will be made available by Makeig, Vankov and colleagues at UCSD for use by Alliance members.

C.2. Data acquisition and management infrastructure will be fully implemented and integrated with a centralized database for all Alliance members to access and for use in the Simulation phase of the experimentation. Beta phase releases of a subset of tools for mining, visualization, and analysis will be made available for Alliance members as well as other DoD laboratories. Initial scenario development will be complete for the simulation experiments and scenarios will have been assessed on pilot data.

C.3. All data will be collected for the Simulation phase experiments by the end of the first quarter of year 4. All data generated during the Simulation phase experiments will be submitted to the CaN CTA database for archival as well as analysis activities. New and revised requirements and specifications for the CaN CTA tool set will be defined and agreed upon.

C.4. A suite of CaN CTA tools for brain imaging and neurocognitive performance assessment will be released in full form, following integration of feedback from Alliance members and other DoD laboratories. Real-time acquisition, reduction, and analysis toolset will be delivered for integration into Army test-bed.

C.5. A full suite of tools for both online and offline acquisition, processing, and analysis will be delivered to and integrated with Army test-bed systems.

4.2.4 TE II. Transitions

The purpose of this TE is to provide hardware and software tools that will enable advanced monitoring of Soldier performance in operational environments as research evolves from laboratory to simulation to real-world settings. In particular, the objective of this TE is to provide tools necessary for the implementation, integration, and interpretation of MoBI into real-world environments and the integration of MoBI into DoD systems. More broadly, the transitioning of advanced tools for the acquisition, reduction, visualization, and mining of high-density information regarding brain and behavioral dynamics will enable vast changes in the ability to conduct research within real-world, operationally relevant environments. However, the

tool developments envisioned to be advanced within this TE must be matured before longer-term transitions can be realized. For example, beyond the definition and development of hardware and software supporting the implementation of advanced acquisition, reduction, visualization, and mining capabilities is the enhancement of system usability and robustness for breadth of application across user groups and testing/evaluation environments, including ruggedization for use in operational environments. Ultimately, the efforts under TE II will lead to later transitions influencing the advanced design of crew station systems and real-time Soldier monitoring applications. By enabling investigations of brain function in complex dynamic environments, this will facilitate discovery of previously unexplored relations among multiple brain, behavior, and environmental variables targeting new insights to old problems, and contribute to the advancement of theories of human performance, and contribute to more comprehensive and accurate models of Soldier performance that will better serve the Army across a variety of task domains.

4.3 TE III. Enhanced Design of High-information Multichannel Crew Stations

Advances in enabling technologies are enhancing Soldier-system performance and expanding operational capabilities; however, these advances are also intensifying the need for Soldiers to operate in complex, mixed-initiative system environments in which dynamic, complex information streams must be integrated across multiple spatial and temporal scales. Technological advances, particularly in sensor deployment, information bandwidth, and automation, coupled with economic and political realities, continue to place more and more responsibility on fast, distributed, and effectively independent decisions by solo or small groups of Soldiers who control ever more potent defensive and offensive assets. Under such circumstances, Soldier cognitive failures in comprehension and decision making based on ever more complex data streams can become a critical bottleneck in Army defensive and offensive capabilities. The CaN CTA research program aims to develop neuroscience-based principles that focus on how best to assist people to operate in complex, mixed-initiative system environments in which dynamic, complex information streams must be integrated across multiple spatial and temporal scales. This TE focuses on prototype high-information multichannel crew stations that reflect the complex socio-technical environments envisioned above. Specifically, the TE integrates the basic science and neurotechnology efforts over the course of the CaN CTA into a prototype Warfighter-machine interface (WMI) to enhance Soldier-system and team performance.

4.3.1 TE III. Background

As Future Force concepts have evolved in the direction of employing computationally intelligent architectures to compliment and supplement Soldier abilities, concepts and methods regarding the acquisition and use of information have become increasingly central. The focus of these concepts demands continued attention towards improvement of the means and methods by which information is both transmitted to and collected from the Warfighters. That is, as a focal point of

continued efforts, emphasis on the interfaces between Warfighter and system is not only warranted, but, in fact, is a critical element of future-oriented S&T programs. Through a variety of programs, the U.S. Army has made considerable investments into the development of Soldier-machine interface technologies to support the conduct of military operations. With research and development efforts beginning as early as the mid 1980s (i.e., on the Inter-Vehicular Information System [IVIS] fielded in the M1A2 Abrams), military interface technologies have evolved through literally decades of research, development, and engineering evaluations as well as through, for some systems (e.g., IVIS, Force XXI Battle Command, Brigade-and-Below [FBCB2]), use in-theater (Morrison et al, 2003). Currently, TARDEC, along with its partners, including ARL, the U.S. Communications-Electronics Research Development and Engineering Center (CERDEC), and the Night Vision and Electronic Sensors Directorate (NVESD), is continuing development of crew station solutions for WMI technologies, an example of which is shown in figure 5.

Figure 5. Example of crew station technology developed to optimize Soldier workload and provide the ability to conduct mission planning; route planning; reconnaissance, surveillance, and target acquisition (RSTA); and fire control capabilities. The crew station WMI software is fully configurable (up to six possible independent screens may be displayed simultaneously), portable (between crew stations), and interoperable. Here, two crew stations are shown as mounted on a large 6 DOF motion simulator located at TARDEC.

The modern direction of WMI development is towards highly complex, mixed-initiative system environments. For example, a vision of the future environment includes a highly networked "family" of tactical assets including both manned and unmanned ground and aerial vehicles along with remote sensing and weapons capabilities. In this vision, the WMI is to provide the ability for individual Soldiers to have access to broad-area informational resources developed from those assets in order to perform one of over 100 possible predefined roles. Therefore, modularity and flexibility of interface design have been essential.

At the same time, however, to avoid heavy training burdens, it has been seen as desirable to have a WMI that shares common features and functionality across roles and tasks. The flexibility of current TARDEC-ARL crew station solutions results in tremendous functionality that includes imagery that makes relatively large, prominent screen space claims, (e.g., vehicle teleoperation displays, mission planning, vehicle sensor controls, local area and 3-D situational awareness monitoring, multiple-vehicle formations control, robotics control asset list) and secondary functions that can be minimized to preserve screen space (i.e., asset maps, route plan maps, and warnings, cautions, and alerts [WACAs]).

Beyond human factors considerations that have driven the screen design concepts, layout, and functionality built into the current TARDEC-ARL crew station solutions, the CaN CTA research will enable systems designers to address a variety of critical high-level functions that have yet to be fully and successfully addressed by enabling technologies integrated with prior WMIs.

Secure mobility

Secure mobility is a concept that was created to help capture, in a descriptive sense, the key differences in the management of vehicle mobility between civilian and military task contexts (McDowell, Oie, Tierney, and Flascher, 2007; McDowell, Nunez, Hutchins, and Metcalfe, 2008). In the civilian context, the goals associated with driving include, at a high level, path selection, position maintenance, and safety (collision avoidance) for those inside the vehicle as well as those outside (pedestrians, other vehicles). In the military context, however, in addition to the concerns associated with basic driving and navigation, Soldiers have the added expectation of maintaining local area awareness sufficient to detect threats to their own safety and that of their platoon, as well as any semiautonomous (robotic) assets that they may be within their purview. Therefore, there are added demands and dynamics to military mobility tasks that do not exist in standard civilian driving conditions. Further, an important contribution to the cognitive dynamics of secure mobility, as it is typically executed under current force operations, is that of team function. That is, because of the complexity and level of threat associated with military environments, secure mobility is currently treated as a team function in that one Soldier monitors navigation, another drives the vehicle, and yet others serve as look-outs responsible for different sectors of observation across the 360° surround. Tools and techniques are thus needed to enhance abilities to efficiently and effectively maintain secure mobility during military operations.

Complex and Multitasking Environments.

Indeed, military environments are highly complex and dynamic. More to the point, the range of variability associated with military operational environments is quite vast. Operational tempo (OPTEMPO), for example, can vary from extremely slowly changing dynamics, such as in scenarios involving the need to manage persistent stare over extremely protracted periods of time (i.e., surveillance over a potential enemy base for days on end), to extremely rapidly developing

dynamics, such as in the midst of an armed confrontation with enemy combatants intermingled with civilian bystanders. Of course, OPTEMPO is but one of many variable factors that influence the technologic needs of the Soldier situated in theater; variable constraints affecting communications, visualization, cognitive, and physical fatigue; maintenance of a common operating picture; and so on limit the abilities of the individual Soldier in the modern threat environment as well as drive the need for technologic enhancements to the WMI. Beyond the multimodal complexity affecting mission dynamics is the fact that the modern Soldier will be expected to function adaptively under the pressures of maintaining performance on multiple, temporally overlapping and, in some cases, competing tasks—each with their own variable dynamics. Examples of overlapping tasking may include monitoring of several (intra- and inter-vehicular) communications streams, monitoring and control of one or more unmanned tactical assets (both aerial and ground assets), and monitoring streams of (mostly visual) data forming the common operating picture, along with other RSTA activities.

Platoon Leader (PL) Decision-Making

In the U.S. Army, a mechanized platoon of light or heavy armored vehicles can consist of number of Soldiers and a variety of equipment. An M1 tank platoon can typically contain four tanks with four crew members in each tank (tank commander, gunner, driver, and loader). One of the tank commanders would also be the leader of the platoon. A platoon of mechanized infantry in Bradley Fighting Vehicles would contain four vehicles with 10 Soldiers in each. Some of the Bradley platoon Soldiers will have mounted roles and some will have dismount roles, but all will be commanded by the platoon commander. Such platoon organizations are further grouped into companies made up of three to four platoons with additional staff and equipment for company Headquarters. Therefore, decisions to be made at the PL command echelon affect and are affected by both top-down and bottom-up elements of the command structure. In order to make adequate decisions at the PL level, one must be aware of the state of subordinate troops, the local operational environment, the state of the company, as well as orders and constraints communicated downstream from higher echelons. The WMI, therefore, must also provide sufficient capability to simultaneously monitor all relevant aspects of the informational environment. Given the complexity of the typical military operational context, information presented to the PL should not be presented in the form of raw data (i.e., raw video screens, unfiltered audio, etc.), but rather should be processed, summarized, and/or enhanced to facilitate immediate comprehension for the sake of time-pressured decision-making.

Team Dynamics/Cooperation

As with secure mobility discussed previously, many military tasks conducted in the operational environment involve a division of roles with an aim towards integration of outcome. That is, military tasks are commonly subdivided into smaller sets of roles to be assigned to different

members of a platoon or vehicle crew under the concept that as each Soldier fulfills his or her role, the overall mission will be brought to completion. What this presumes, however, is that all members of the team/platoon/squad share, in continuous real-time, the same essential cognitive ingredients (i.e., information, attention, motivation, intent, etc.) for assembling the necessary orderly plan of action for completing the assigned task or tasks. Moreover, to add to the complexity of cooperative tasks, certain military concepts assume that tasks broken into subcomponents in this way can be completed by teams of non-co-located Soldiers (e.g., target acquisition and engagement). Thus, differing perspectives/frames of reference on the problem environment as well as the dynamics of potentially imperfect communications streams have the potential to alter (or at least dramatically complicate) the ability of such teams to operate effectively and efficiently when conducting distributed team actions.

Brain-system Interface

Finally, the ideal concept for "closing the loop" between Soldier and system through a well-designed interface is to provide a means of feeding data regarding the neurocognitive state of the Soldier into the WMI that is being used. Such an achievement would be a major advance over current action-based (e.g., button pressing) methods of providing Soldier feedback to the system function as it would not rely on awaiting appropriate overt action from the Soldier alone; the system could function based, in part, on the neurocognitive data that it received from monitors of Soldier physiology and behavior. This inherently suggests that data regarding the moment-to-moment dynamics of brain function (i.e., "brain waves" or EEG patterns) should be integrated with WMI function. However, under the concepts of MoBI as discussed earlier, a true "brain system interface" must include more than EEG data; it must also include data regarding the behavior that is being optimized and controlled by brain function. Therefore, information regarding Soldier/operator behavior and appraisal of the stimulus environment to be gained from measurement of gaze point location, bodily action, and autonomic function (e.g., heart rate, respiration) should be integrated with the WMI in addition to EEG for the efficient leveraging of neurocognitive signatures for enhancing overall system performance.

4.3.2 TE III. Transition Barriers and Hurdles

As already established, the development of Soldier-machine interface technology spans several decades of science and engineering efforts. Starting as early as the 1980s, military interests have funded the development of technologies to provide battlespace information to Soldiers that are located within vehicles designed to simultaneously enhance both survivability and lethality. In the CaN CTA, however, efforts are planned to take a new direction in enhancing previous WMI design concepts for modern-era military use. That is, the research and development efforts within the CaN CTA will build on previous WMI concepts to integrate the Soldier and the system in ways that have not yet been achieved for fielded systems. The high-information, multichannel crew station to be prototyped through the CaN CTA will be among the first of its kind to place Soldier and system on equal footing as members of the same team—with the

system leveraging "knowledge" regarding the state of the Soldier to take action that facilitates the Soldiers ability to complete operational tasks both efficiently and effectively. In order to develop such a prototype system, then, this preplanned TE will have to build from the early progress made in crew station interface design in addressing all five primary scientific barriers:

B.1 The restriction of experimental designs to highly controlled and impoverished stimulus/response paradigms and environments.

Experimental environments must advance beyond those typically developed for highly controlled and impoverished laboratory settings. WMIs developed need to be matured and validated as robust enough for application in highly complex environments, multi-tasking scenarios, or for operation in multiple or fluctuating performance domains such as PL decision making and secure mobility.

B.2 The lack of portable, user-acceptable (e.g., comfortably wearable), and robust systems for monitoring brain and body dynamics.

Multi-purpose acquisition systems need to able to collect *high-fidelity* EEG data robustly and continuously without the use of conductive gels or skin preparation. Further, portable systems must robustly handle the expected substantial, in-vehicle electrical and motion artifacts that pose threats to reliable and valid recording of brain dynamics in operational environments.

B.3 The failure to record the whole of physical, mental, and physiological behavior that the brain controls, and the physical and socio-cultural effects of the environment that impact brain function, in sufficient detail and across a sufficient breadth of circumstances.

Data acquisition systems must be generic or adaptable enough to collect data in the sufficient detail and across a breadth of circumstances and in conjunction with a variety of interface configurations supporting a number of military roles. Such systems must incorporate a wide range of sensor technologies and thus must address issues associated with sampling rate, synchronization, data storage, subsequent data retrieval, and overall data flow between system components. Specifically, multi-aspect datasets collecting high-density data from differing types of physiological sources (e.g., EEG, EMG, eye and body movements) are often very large and unwieldy in raw form.

B.4 The lack of mathematical modeling methods and software to find statistical relationships between moment-to-moment variations in environmental, behavioral, and functional brain dynamic recordings.

Due to the novelty and the scale of the large, multi-aspect datasets expected from within operationally relevant scenarios, new tools for data-reduction, mining, and visualization must be developed. In particular, as systems progress towards real-time implementations, such tools must enable developers to constrain system designs to utilize only the necessary and sufficient data as opposed to online mining and processing of overwhelming amounts of data. Moreover,

in order for such information to be most useful in the crew station context, adequate and advanced methods for summarizing complex data need to be explored alongside methods for efficient and effective communication of complex multichannel (visual, auditory, text-based) data streams.

B.5 The lack of sufficient data archives and resources to systematically study relationships between individualized models derived for cognitive monitoring and individual differences in performance, cognitive ability, and personality, relationships that could optimize performance of cognitive monitoring systems while lowering requirements for collecting individual subject training data.

The WMI designed and tested under TE III should be able to use models of brain/behavioral changes that do not require extensive pilot training data from each Soldier, while respecting operator differences in, e.g., baseline EEG that may be present in recordings from each new Soldier subject. Applied studies under TE III using a number of subjects will allow early investigation within the CTA of the extent to which individualized data models perform better than a common data model, while computational approaches to characterizing relationships between individual and group data, developed under B.5 will allow first testing of methods to quickly individualize a common model from partial (baseline) EEG data on each individual.

In addition to the scientific barriers, the translational process will have to address technical challenges related to the specific operational topics discussed above. The primary technical challenges that the enhanced design of high-information multichannel crew stations TE will face are as follows:

- Crew station interfaces must provide data and visualization tools sufficient for maintenance of real-time local area awareness during vehicle mobility control. Such tools may include, but are not necessarily limited to, those supporting semi-autonomous navigation, which has the potential to alleviate demands on driver perception and attention during execution of simultaneous mobility and security tasks (McDowell et al., 2008) so as to enable execution of secure mobility functions.
- Crew station interfaces must provide communications tools sufficient for maintenance of real-time situational awareness during multitasking and teaming/cooperation. In both multitasking and teaming/cooperation scenarios, maintenance of situational awareness is essential—allowing the operator to construct and hold mental representations of task status during execution of potentially discontinuous, irregular OPTEMPO operations under constraints of partial information feedback.
- A key aspect of decision making is the ready access to the information necessary for arriving at an optimal choice among a limited set of viable operational options. Therefore, to support decision making, both advanced intelligent architectures (including autonomous agents) and real-time communications and visualization enhancements will necessarily

need to be integrated. The combination of enhanced informational systems supporting real-time situational awareness with intelligent architectures designed to assist decision making (e.g., an "expert system" that summarizes data and prioritizes potential actions), especially as complimented by integrated data regarding the neurocognitive states of each Soldier in a PL's command, has considerable potential to ease and economize decision making when in time-pressured operational circumstances.

4.3.3 TE III. Translational Timeline

As shown in figure 6, seven primary Alliance research topic areas feed into this TE:

1. First, it will be necessary to integrate the novel data acquisition, reduction, and mining tools from TE II into the crew station as they become available through CaN CTA efforts. The existence and integration of such tools for assessment and characterization of Soldier neurocognitive state and performance will serve as a foundation on which progress in the remaining focus areas will rest.
2. We will develop and integrate tools to advance Soldier capabilities to execute secure mobility functions using the WMI.
3. In a parallel effort, the CaN CTA will develop and assess new WMI technologies for enhanced performance in complex, multitasking environments (including secure mobility functions).
4. In a similar parallel effort, the Alliance will address the challenge of providing technologies to enhance PL-level decision making in operational environments.
5. We will examine communications tools for facilitating team performance during execution of cooperative tasks.
6. The Alliance will work to integrate the above five efforts with one aimed at developing and refining MoBI-derived brain-machine interfaces for enhancement of Soldier-system performance using neurocognitive data.
7. During the fifth program Year, all of the above described efforts will culminate in an area of focus that will develop a prototype, proof-of-principle WMI that integrates neuroscience-based design elements, or neurotechnologies.

There will be one main transition that results from efforts in the seven focus areas, that is, the tools, techniques, and technologies developed through CaN CTA efforts in general, as well as from TE III in particular, will result in a prototype high-information multichannel crew station to be integrated with an Army vehicle test-bed system. The multichannel crew station will support advanced visual displays, audio and text-based communications, brain-machine interfaces, and automation for enhancing Soldier-system performance in the areas of secure mobility, multitasking support, teaming/cooperative mission execution, and decision making.

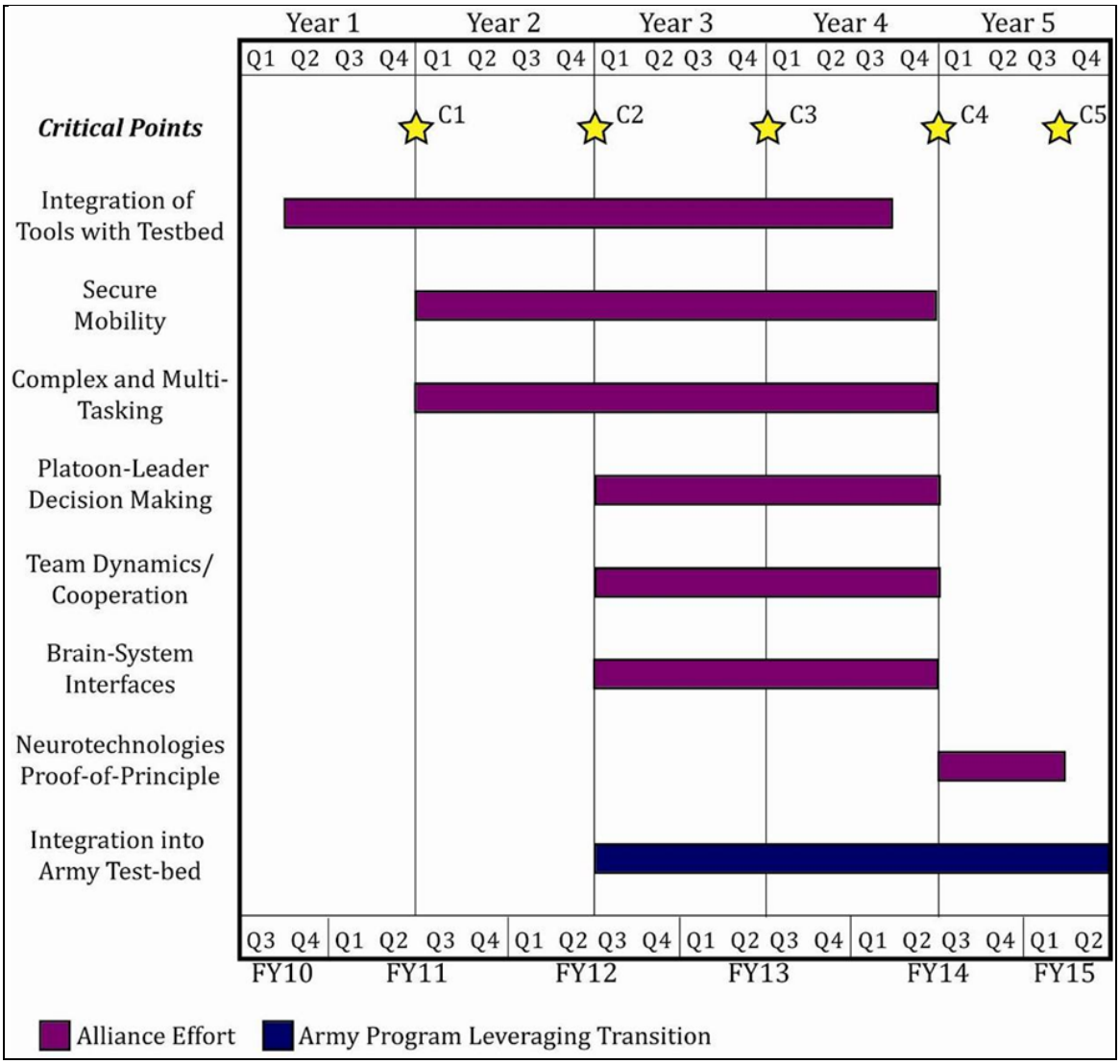

Figure 6. Translational timeline depicting expected progress in TE III.

The high-information multichannel crew station TE illustrates a progressive process to be metered out across the duration of the CaN CTA program period. In year 1, the focus in TE III will be on the integration of advanced tools from TE II as they are matured to the point where they may be used in the crew station environment. Year 2 will then begin focus on applying the advanced tools to the high-level objectives of establishing tools for facilitating goals associated with secure mobility as well as enabling performance in complex, multitasking environments. Year 3 onward will then see the enhancement of the crew station environment and associated tools for use in team dynamics and decision making, as well as integration of MoBI-derived tools for brain-system interfacing. Further, from year 3 onward, efforts will aim towards integration of tools and techniques with crew stations in Army test-bed environments. In the final year, proof-of-principle neurotechnologies will be integrated to complete the final transition of a high-information multichannel crew station prototype for use in complex military environments.

These efforts are described in the Alliance research projects supporting this transition, which include the following:

- The Construction and Use of Cognitive Maps Under Threat (CMT)
- DAS
- Constructing Mutually-derived Situational Awareness via EEG-informed Graph-based Transductive Inference (GTI)
- MBF
- Modeling Perceptual Decision Making (MDM)
- Multi-Modal Sensory Attention (MSA)
- MSS
- Using Neural Biomarkers to Predict and Guide an Individual‘s Ability to Optimally Adapt Decision Rules (NBD)
- Optimal Decision Making (ODM)
- ODE
- Using Neural Activity to PAL
- Perceptual Integration Across Time and Modality (PTM)
- SCN

In addition to the research projects, this TE will require additional specific efforts to address the technical challenges.

- From Year 3 onward, as tools approach completion ARL will lead an effort, in collaboration with DCS Corp, to evaluate developed tools, techniques, and interface technologies for general usability and appropriateness for research laboratory and in-field utilization.

Critical Points

There are five critical points in the successful completion of this project.

C.1 The ERICA/DataRiver data acquisition system will undergo initial integration with ARL/TARDEC crew station test-bed. In particular, efforts will focus on issues affecting synchronization and storage of high-density, multimodal data to be obtained using paradigms developed under the MoBI concept.

C.2. A preliminary scenario concept will be developed for assessment of crew station functionality in final capstone phase experiments. A gap analysis, focusing on discrepancies between simulation phase and final capstone phase experimental scenarios will be completed.

C.3. Gaps between simulation phase and final capstone phase experimental scenarios will be investigated. Principles and concepts for implementation in neurotechnologies proof-of-principle will be identified and development requirements will be specified.

C.4. Scenarios for final capstone phase experiment will be finalized and piloted. Brain-system interfaces designed for integration with the proof-of-principle neurotechnologies will be available.

C.5. Test and evaluation of the neurotechnology prototypes in crew station test-bed will take place. All prototype hardware/software and results will be delivered to the transition customer.

4.3.4 TE III. Transitions

The objective of this TE is to develop and deliver a prototype crew station system that will advance WMI technologies beyond those designed under traditional systems, software, and human factors engineering concepts. Specifically, as systems have been typically developed, end users have only been considered during system design at two levels: (1) when specifying the goal state for the system in terms of user functionality and (2) in designing the interface once the system and its functionality have been defined and largely developed. Yet, in terms of the actual mechanisms of system function, generally speaking, the needs of (and potential contributions from) the user have largely been subordinated to the engineering challenges encountered during system design and development. From a neuroergonomic standpoint, however, it is considered to be advantageous to account for users and their functional properties (i.e., neurocognitive function) *from the outset of and throughout the process*. As such, the goal of this TE is to leverage tools (hardware and software) and techniques as developed through CaN CTA research efforts in general, as well as from the other two TEs in particular, to enhance performance on a selected set of functions that include secure mobility, complex and multitasking environments, PL decision making, and team dynamics and cooperation. Such technologies for leveraging aspects of neurocognitive function will be realized through brain-system interfaces that enable proof-of-principle neurotechnologies to be instantiated in an Army test-bed system. By enhancing the design of WMIs in this fashion, it is expected that the activities executed under this TE will bring future force concepts closer to their ultimate realization in crew station systems.

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Appendix. Listing of Projects and Principal Investigators

Table A-1 is a list of the projects and their principal investigators.

Table A-1. Projects and principal investigators.

Project Title	Project ID	Principal Investigators	Project Keywords
TA1: Neurocognitive Performance			
Ambulatory Neuroergonomics	ANE	Dr. Dan Ferris, U. Michigan Dr. Jason Metcalfe, DCS Corp	Locomotion, Motor control, Lower-limb dynamics
Construction & Use of Cognitive Maps Under Threat	CMT	Dr. Chin-Teng Lin, NCTU Dr. Peter König, U. Osnabrück	Spatial cognition; Spatial navigation; Multisensory integration;
Large-Scale Experiments	LSE	Dr. Scott Makeig, UCSD	Attentional Switching, Multitasking, Individual Differences
Modeling Perceptual Decision Making	MDM	Dr. Angela J. Yu, UCSD	Cognitive modeling, Individual differences, Bayesian predictive models, Perceptual contingency learning
Multi-modality Sensory Attention	MSA	Dr. Peter König, U. Osnabrück	Multisensory integration, Attention allocation, Tactile displays
Multi-screen Search	MSS	Dr. Klaus Gramann, U. Osnabrück Dr. Jason Metcalfe, DCS Corp.	Visual search, Internal reference frames, Multi-modal sensory inputs, Situational awareness
Using Neural Activity to Predict and Guide an Individual's Ability to Optimally Adapt Decision Rules *	NBD	Dr. Michael Miller, UCSB Dr. Barry Giesbrecht, UCSB Dr. Scott Grafton, UCSB Dr. Jean Vettel, ARL	Signal detection theory, Optimal decision making, Individual differences
Operator Dynamics of Event Appraisal	ODE	Dr. Jason Metcalfe, DCS Corp Dr. Stephen. Gordon, DCS Corp Dr. W. David Hairston, ARL Dr. Will Nothwang ARL	Event appraisal; Facial expression; Affective response; Multisensor fusion
Using Neural Activity to Predict Attentional Lapses During Multisensory Task Scenarios*	PAL	Dr. Daniel Weissman, U. Michigan Dr. Barry Giesbrecht, UCSB Dr. W. David Hairston, ARL	Machine learning, Performance prediction, Attentional lapses
Speech Comprehension and Neurolinguistics	SCN	Dr. Roger Levy, UCSD	Semantic processing, Neurolinguistics

*- Year 2 Seedling award. Seedling projects are awarded based on competitive solicitation to address specific issues identified as priorities for the Army. Project proposals can be up to three years in duration, and are reviewed annually.

Table A-1. Projects and principal investigators (continued).

Project Title	Project ID	Principal Investigators	Project Keywords
TA2: Neurocomputation			
Connectome-based Advancement of Brain Analysis*	CBA	Dr. Walter Schneider, U. Pitt Dr. Don Krieger, U. Pitt Dr. Jean Vettel, ARL	Individual differences, Diffusion weighted imaging, Structure-function coupling
Dynamics of Attention Shifting	DAS	Dr. Scott Makeig, UCSD Dr. Jeanne Townsend, UCSD	Selective attention, Cortical dynamics
Data Fusion, Summary, and Visualization	FSV	Dr. Kay Robbins, UTSA Dr. Nandini Kannan, UTSA Dr. Yufei Huang, UTSA	Data visualization, Database design
Neurocomputation	NCP	Dr. Kenneth Kreutz-Delgado, UCSD Dr. Roger Levy, UCSD Dr. Angela J Yu,, UCSD Dr. Scott Makeig, UCSD	Independent component analysis (ICA), Statistical modeling, Adaptive Mixture ICA (AMICA)

*- Year 2 Seedling award. Seedling projects are awarded based on competitive solicitation to address specific issues identified as priorities for the Army. Project proposals can be up to three years in duration, and are reviewed annually.

TA3: Neurotechnologies			
Constructing Mutually-derived Situational Awareness via EEG-informed Graph-based Transductive Inference*	GTI	Dr. Paul Sajda, Columbia U. Dr. Brent Lance, ARL	Rapid Serial Visual Presentation,
MoBI-based Feedback for Training of Automated Systems and System Operators	MBF	Dr. Scott Makeig, UCSD	Brain-computer interaction, Adaptive systems, Training
Effects of Vehicle Motion and Cognitive Fatigue	VMF	Dr. Chin-Teng Lin, NCTU Dr. Tzyy-Ping Jung, UCSD	Brain-computer interaction, User monitoring, Data acquisition, Real-time data processing
Wearable EEG Development and Testing	WDT	Dr. Chin-Teng Lin, NCTU Dr. Tzyy-Ping Jung, UCSD	Wearable systems, Sensor development

*- Year 2 Seedling award. Seedling projects are awarded based on competitive solicitation to address specific issues identified as priorities for the Army. Project proposals can be up to three years in duration, and are reviewed annually.

List of Symbols, Abbreviations, and Acronyms

3-D	three-dimensional
AgCl	silver chloride
ARL	U.S. Army Research Laboratory
BCI	brain-computer interface
CaN	Cognition and Neuroergonomics
CTA	Collaborative Technology Alliance
CERDEC	U.S. Army Communications-Electronics Research, Development and Engineering Center
CES	Command Environment Simulator
CMT	Cognitive Maps Under Threat
DAS	Brain Dynamics of Attention Shifting
DCS	DCS Corporation
DOD	Department of Defense
DoF	degrees of freedom
ECG	electrocardiography
EEG	electroencephalograM
EMG	electromyography
ERC	Experimental Real-time Control
ERICA	Experimental Real-time Interactive Control and Analysis
FBCB2	Force XXI Battle Command, Brigade-and Below
fMRI	Functional Magnetic Resonance Imaging
FSV	Data Fusion, Summary, and Visualization
GI	Graph Invariant
GTI	Graph-based Transductive Infrerence
IC	independent component

ICA	Independent Component Analysis
IED	improvised explosive device
IVIS	Inter-Vehicular Information System
MBF	MoBI-Based Feedback for Training Automated Systems and System Operators
MDP	Markov Decision Process
MEMS	microelectromechanical system
MoBI	mobile Brain/Body Imaging
mocap	motion capture
MOM	Modeling Perceptual Decision Making
MR	magnetic resonance (imaging)
MSA	Multi-modal Sensory Attention
MSS	Multi-Screen Search
NBD	Using Neural Biomarkers to Predict and Guide an Individual's Ability to Optimally adapt Decision Rules
NCP	Neurocomputation
NCTU	National Chiao Tung University
NVESD	Night Vision Electronic Sensors Directorate
ODE	Operator Dynamics of Event Appraisal
ODM	Optimal Decision Making
PAL	Predict Attentional Lapses During Multisensory Task Scenarios
PET	Positron Emission Tomography
PL	platoon leader
PTM	Perceptual Integration Across Time and Modality
RSTA	reconnaissance, surveillance, and target acquisition
S&T	science & technology
SBL	sparse Bayesian learning
SCN	Speech Comprehension and Neurolinguistics

TA	Technical Area
TARDEC	U.S. Army Tank Automotive Research Development and Engineering Center
TBL	tramatic brain injury
TE	Transition Effort
UCSB	University of California Santa Barbara
UCSD	University of California San Diego
UTSA	University of Texas San Antonio
VMF	Effects of Vehicle Motion and Cognitive Fatigue
VR	virtual reality
WACA	warnings, cautions, and alerts
WDT	Wearable EEG Development and Testing
WMI	Warfighter-Machine Interface

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