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THE UTILITY OF RIDE MOTION SIMULATION IN A NEUROERGONOMIC APPROACH TO SYSTEMS DESIGN

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ABSTRACT

The complexity of the current and future security environment will impose new and ever-changing challenges to Warfighter capabilities. Given the critical nature of Soldier cognitive performance in meeting these increased demands, systems should be designed to work in ways that are consistent with human cognitive function. Here, we argue that traditional approaches to understanding the human and cognitive dimensions of systems development cannot always provide an adequate understanding of human cognitive performance. We suggest that integrating neuroscience approaches and knowledge provides unique opportunities for understanding human cognitive function. Such an approach has the potential to enable more effective systems design – that is, neuroergonomic design – and that it is necessary to obtain these understandings within complex, dynamic environments. Ongoing research efforts utilizing large-scale ride motion simulations that allow researchers to systematically constrain environmental complexity are then discussed.

INTRODUCTION

Today, our armed forces face a security environment that is more complicated than ever. In its analysis, the Office of the Chairman of Joint Chiefs of Staff [1] identified three key aspects of the security environment that will drive the development of operational capabilities and concepts needed to ensure success on the battlefield now and into the future: 1) A wider variety of adversaries, which includes both state and non-state actors (e.g., terrorist networks, international criminal organizations). The ability of commanders and decision makers to understand motivations and intentions across this wide range of adversaries, to predict their threat actions, to detect their movements, and to do so in time to implement preventative measures will be critical; 2) A more complex and distributed battlespace, which stretches from the Americas to Asia, encompassing widely diverse operational theaters whose terrain can impose dramatically different demands on Soldiers. The distributed nature of the battlefield requires effective coordination and synchronization among several, often physically separated, tactical and strategic bases of command operations among joint, interagency, multinational, and international organizations; and 3) Technology diffusion and access that has the potential to provide new capabilities for our forces, but that may impose new demands on the Soldier and may provide new disruptive and destructive capabilities for those who threaten the United States, its allies, and its interests. Within such a context, understanding how the increased complexity of the current security environment will impact Soldier behavior and performance is fundamental to the design of systems that can maximize Soldier-system performance. Obtaining such understandings, however, presents significant challenges.

Consider, for example, one of the widely-believed approaches to addressing the increased complexity of the current and future security environment: advanced computing and information technology [2]. There is no doubt that computer and information technologies have increased dramatically in recent years: the amount of new, stored information about doubled over the period between 1999 and 2002 and about 18 exabytes of information (i.e., 18 x 1018 bytes of information) were transmitted over telephone, radio, television, and internet communications lines in 2002 [3]. While such capabilities have been conclusively shown to increase human productivity (e.g., [4,5]), they also have changed both the skills and concepts needed to deal with new technologies and information-intensive operations [6.7] and imposed new and significant demands on human information processing capabilities.

By contrast, in the face of these dramatic technological advances and the concurrent increases in information processing demands, the human brain, despite its vast complexity, remains severely capacity-limited (e.g., [8,9,10,11]). It follows that, given the critical nature of Soldier cognitive performance needed to meet the increasing demands of the current security environment, it is the human brain's finite cognitive capacities and limited information processing capabilities that are the bottleneck in information-intensive operations (cf., [12]). Such limits will only be exacerbated under the fast-paced, high-stress conditions of military operations (cf., [13]). Therefore, one of the major goals of technology developers should be to design systems that can work in ways that are consistent with how the human brain functions best and how it deals with information across the wide range of tasks Soldiers must accomplish. Such an approach aims to enhance Soldier-system performance through improving the sociotechnical interactions between operators and the systems they use, augmenting their capabilities where they are weakest and capitalizing on their strengths where technological solutions alone will not suffice.

TOWARDS A NEUROERGONOMIC DESIGN APPROACH

Unfortunately, the general model for technological development has not taken the approach outlined above. Instead, the model has largely been to allow technologies to advance essentially unfettered and to depend upon the capabilities of the human operator to adapt to the latest innovations. Traditional human factors, cognitive psychology, and engineering approaches, where applied, have often been successful in addressing the cognitive-based needs of technology development. The increased information-intensity of the current and future security environment, however, is likely to challenge Soldier cognitive capabilities in ways never before imagined. Therefore, we argue here that new approaches to understanding human cognitive performance are needed to augment traditional approaches and to enable effective systems design that can meet the demands of the dynamic, complex operational environments that Soldiers will face.

Let us consider the assessment of cognitive or mental workload, a typical cognitive performance construct in systems design research (e.g., [14]). Here, workload is understood in terms of the relationship between the demands of a task and the operator's (cognitive) capacity for meeting those demands: When task demands are small relative to the operator's capacity to meet them, workload is low. When task demands are nearly equivalent to the operator's capacity, workload is high. When task demands exceed capacity, the operator is in a condition of cognitive or mental overload.

This definition of cognitive workload, then, requires the consideration of both operator capacity and task demands. Assessing operator capacity has a long and broad history in clinical and research domains, such as in the development of numerous questionnaires and behavior-based test batteries aimed at assessing cognitive abilities (e.g., Cambridge Neuropsychological Test Automated Battery [15], Woodcock-Johnson Tests of Cognitive Abilities [16]), however, a complete discussion is beyond the scope of this short paper.

In terms of task demands, however, traditional methods are limited [17]. Task analysis, for example, can provide insights into task-related causes of high (or low) cognitive workload, but complex task environments including multiple parallel tasks, make it difficult to determine exactly what specific demands are being placed on the operator. For example, the same task may be given different priority at any given time, dependent upon the overall performance goal. Further, the management of time, energy, and available resources needed to accomplish tasks provides an additional cognitive burden that is often difficult to define, let alone quantify.

Performance measures, such as reaction/response times or task completion times, are similarly problematic in complex task environments, where such performance measures often cannot be used to index workload, either overall or for specific subtasks. Veltman and Gaillard [18] argue further that, under such task conditions, operators can adapt to increasing task demands by "exerting additional effort," which may lead to equivalent assessments of task (and therefore, cognitive) performance when assessed through task outcome measures alone. This means that performance-based measures can only provide information on workload when some estimate of the operator's effort can also be indexed. Rating scales, which are generally based upon post-hoc subjective reports of a participant's perceptions of workload or effort, have often been used to provide such estimates (e.g., [19, 20, 21]), but they can be affected by a participant's perceptions and biases and are not well-suited for real-time estimation during task performance.

Measurement of physiological function and state offers an alternative methodological approach to assessing cognitive processing. Central and peripheral physiological measures related to, for example, cardiorespiratory function (e.g., heart rate, heart rate variability, respiration rate; e.g., [22, 23]), as well as more direct measures of overt behavior (e.g., eye and head movements, voice stress; e.g., [24, 25]) offer more objective means of assessment than can be had via traditional performance and rating scale methods, though the sensitivity of such measures can be questioned (e.g., [26]).

One of the potential underlying reasons for this lack of sensitivity is that physiological, and to a similar extent behavioral, measures of cognitive function are only indirect reflections of the brain behaviors that give rise to cognition (for an interesting theoretical treatment, see [27]).

In order to address the shortcomings of traditional methods for cognitive assessment, we suggest that knowledge and approaches from the field of neuroscience hold remarkable opportunities. More and more, the connection between human experience and its basis in nervous system function is the foundation upon which we come to understand how we sense, perceive, and interact with the external world. Over the past several years, the field of neuroscience has experienced explosive growth, providing incredible advances in our scientific understanding of the capabilities and limitations of the human brain. Indeed, it is increasingly believed that exploiting the advances in knowledge about the brain and its function hold the promise to radically improve Soldier-system performance to maintain our tactical and strategic advantages over our adversaries (cf., [28, 29]).

The methods and approaches of neuroscience offer perhaps the best avenue towards achieving understandings of Soldier cognitive performance needed to inform systems designs that are consistent with human brain function; that is, neuroergonomic designs. For example, as a direct measure of the electrical activity of the brain detected at the scalp, electroencephalography (EEG) provides objective measurement that is more closely associated with cognitive function than other psychophysiological measures such as heart rate or respiration. EEG also provides very high temporal resolution measurements, enabling observation and analysis at time scales (~ ms) relevant to the dynamic behavior of the brain, unlike performance measures or rating scales. And while current technologies are still fairly cumbersome to use (e.g., requiring significant setup time and the application of electrolytic gels), technological advances hold the promise both of nearly non-invasive measurement and of real-time analysis of brain activity (e.g., [30]). Advances in computational power and data analytic techniques have also enabled the development and application of novel signal analysis and decomposition methods (e.g., [31,32]), as well as advanced data mining techniques (e.g., [33]) for data processing and knowledge discovery in highly-multidimensional data sets in ways that have clearly surpassed our previous knowledge. In fact, the technological and computational advances discussed above also have the potential to improve EEG technology, enhancing its spatial resolution relative to the current state-of-the-art in neuroimaging technologies (e.g., functional magnetic resonance imaging (fMRI)) and moving neuroscience-based cognitive assessment into real world environments.

For the Army, assessment in operational environments is a critical issue. While the explosive growth in the neurosciences has undoubtedly increased our knowledge and understanding of brain function, much of this discovery has occurred within the highly-controlled environments of the laboratory with tasks that often are not representative of the tasks humans perform in real life. Such constraints, indeed, are required both by methodologies that require the participant to minimize motion as much as possible to maximize measurement fidelity (e.g., fMRI), and by the need to control potentially confounding variables that could affect the interpretation of experimental data. The dynamic, complex nature of Army operational tasks and environments, however, is likely to affect the human nervous system in ways that are significantly, if not fundamentally, different than the tasks and environments traditionally employed in laboratory studies. Therefore, assessing the cognitive demands of human operators during the performance of real-world tasks in real-world environments (i.e., ecological validity) will be critical for understanding how we really behave [34], and such understandings are vital for substantiating the validity of generalizing the results of laboratory studies to more naturalistic behaviors (i.e., external validity).

UTILIZING RIDE MOTION SIMULATION TO ENABLE NEUROERGONOMIC DESIGN

To best address questions of ecological and external validity, observation and quantification of human performance should be accomplished within as realistic environments as possible. However, applying laboratory-based neuroscience methods in the real world, and specifically to the assessment of Soldiers operating within dynamic, complex environments, presents significant technological challenges. One approach to addressing this issue is the use of large-scale motion simulation, which provides researchers with the ability to examine human performance in dynamic complex environments while offering tight control and manipulation of the motions that participants will experience.

Over the past several years, the U.S. Tank Automotive Research, Development & Engineering Center (TARDEC) and the U.S. Army Research Laboratory have been developing these capabilities to address Soldier performance issues during the research and development cycle (cf., [35]). One of the critical capabilities in these efforts has been the utilization of six degree-of-freedom ride motion platforms (e.g., [36, 37]) to simulate manned ground vehicle operations. As illustrated in Figure 1, the TARDEC Ground Vehicle Simulation Laboratory's Ride Motion Simulator

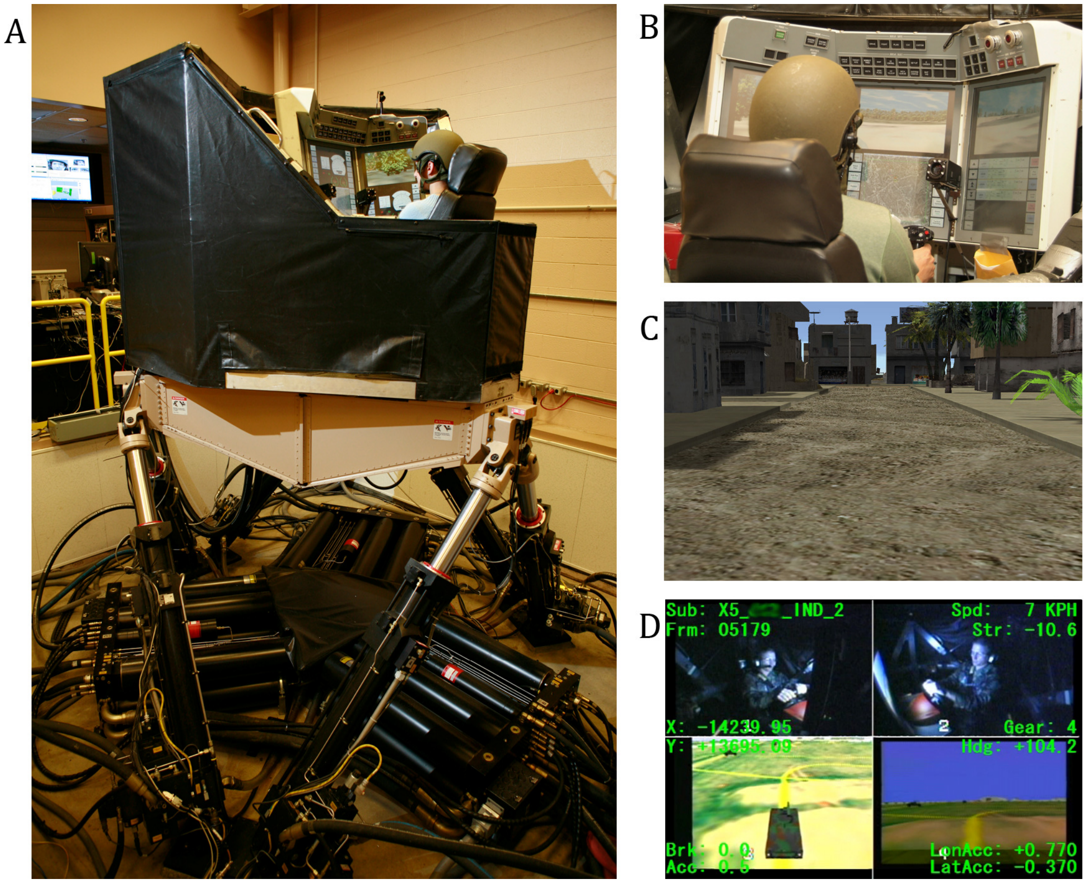

Figure 1. TARDEC Ground Vehicle Simulation Laboratory's Ride Motion Simulator (RMS). A) Re-configurable vehicle cab on the six degree-of-freedom RMS; B) The TARDEC advanced crew station interface; C) Screenshot of urban scenario virtual environment used in RMS vehicle mobility experimentation; D) Data collection system four-input video display. (All images: U.S. Army photo by TARDEC (A,B,D) and ARL (C))

(RMS) is capable of simulating the ride dynamics and characteristics of a wide range of military ground vehicles traversing a vast array of ground terrain surfaces, including secondary roads and cross country terrain. As pictured in Figure 1A, the motion platform supports a reconfigurable cab that is large enough to allow the examination of advanced crew station designs, such as those developed under the TARDEC Crew Integration and Automation Testbed - Advanced Technology Demonstration (CAT-ATD) program (Figure 1B). RMS motion dynamics are specified by an advanced, integrated, real-time, distributed simulation framework and data collection system, which allows researchers to design and model vehicle dynamics, complex virtual scenarios (Figure 1C), and to record both vehicle motion and user control inputs to fully characterize experimental performance (Figure 1D).

We have recently extended these capabilities further to include state-of-the-art measurement technologies with the goal of enabling a neuroergonomic approach to systems design. This has entailed the integration of advanced sensor systems, including (see Figure 2 A-C):

- Non-contact eye- and head-tracking
- Pre-amplified EEG biopotential measurement
- Wearable physiological monitoring platform

Current efforts are also underway to improve measurement system integration, as well as hardware infrastructure for data acquisition and handling. These efforts include integration of sensor and measurement systems with data streams from the RMS's simulated environment, as well as from advanced crew station testbeds, to ensure that data synchronization is optimized across different measurement systems and data classes (cf. [38]).

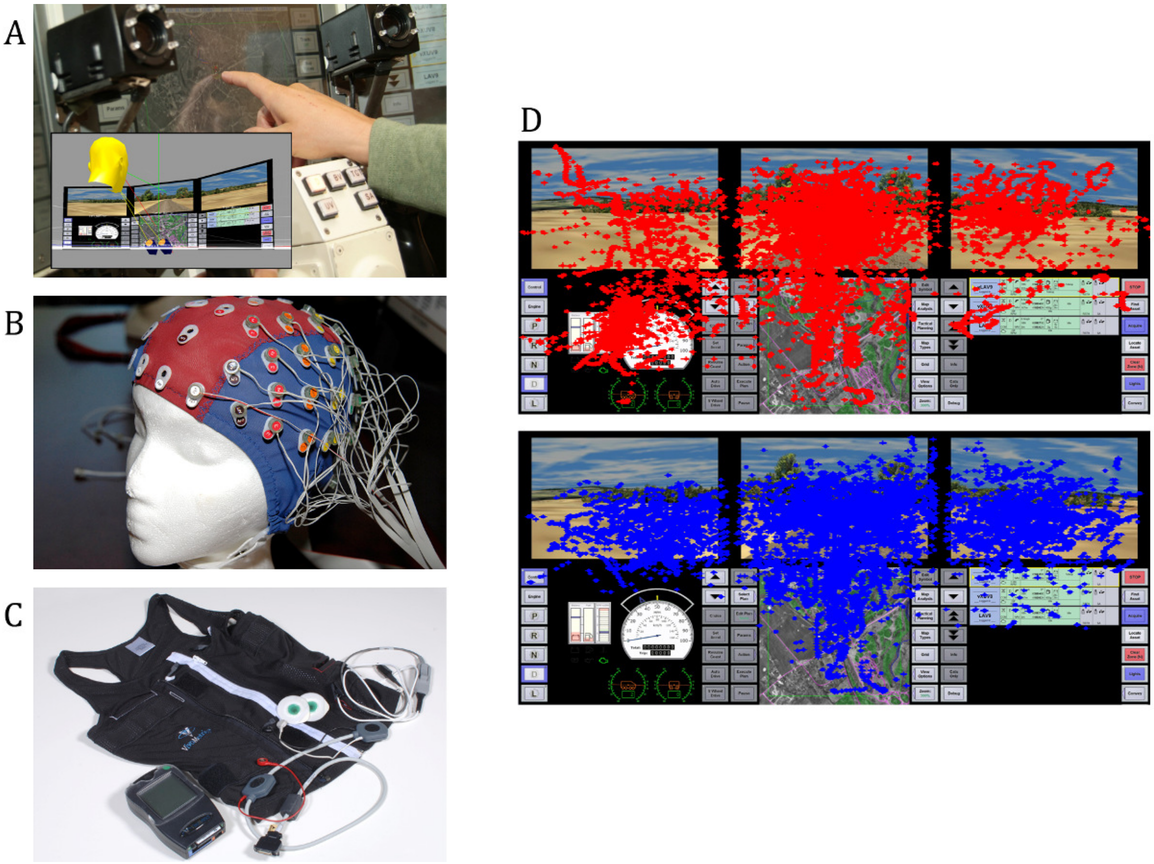

Figure 2. A) Close up of the eye- and head-tracking system cameras mounted on the TARDEC crew station. Insert: screen capture of the world model during active gaze and head tracking; B) Electrode array for the biopotential measurement system for EEG; C) Wearable physiological monitoring system; D) Distribution of gaze fixations during indirect vision driving (upper) and autonomous mobility operations (lower) obtained in the TARDEC RMS (All images: U.S. Army photo by TARDEC (A), ARL (A (insert), B, C, D)

A preliminary implementation of the eye-tracking measurement capabilities now integrated with the RMS was used to show strong differences in visual scanning patterns between manual driving and autonomous mobility using the indirect vision capabilities of the TARDEC CAT crew station (see Figure 2D). It was demonstrated that autonomous mobility capabilities allowed participants to increase visual scanning of the environment for potential threats to maintain local area awareness and maintain security for their vehicle platform (see lower panel of Figure 2d). The results of these pilot investigations were then used to inform the design of field experiments held at Fort Knox, KY.

More recently, a major data collection effort was conducted on the RMS that examined the physiological and neurophysiological responses of participants riding through a virtual urban environment (Figure 2C) under complex task and environmental conditions. Participants scanned the environment for potential threats, identifying friendly and enemy human targets and reported on their type (friendly/enemy), number, and location, while simultaneously supervising the vehicle's autonomous mobility system and intervening when necessary to avoid collisions. Further, additional vibrations (~20 Hz) were added to the vehicle's dynamic (simulated) motion in experimental conditions to examine their effects on visual perception and scanning performance, which are critical for local area security using indirect vision system such as those employed here. Analysis will be aimed at characterizing changes in task, physiological, and neurophysiological behavior in response to both vibration and task demands.

In summary, we have argued that traditional approaches to understanding the human and cognitive dimensions of systems development cannot always provide an adequate understanding of human cognitive performance. We suggest that an approach that integrates neuroscience knowledge and approaches provides unique opportunities for understanding human cognitive function to enable a vision of systems development that can result in systems that work in ways that are consistent with the function of the human brain (i.e., neuroergonomic design), and that do not simply rely upon our ability to adapt to new technological innovations. The understandings necessary for supporting such an approach, then, must be validated through observation and assessment within complex, dynamic environments. The simulation and measurement capabilities discussed here, then, provide unique capabilities for developing the measurement and assessment techniques needed to obtain a proper understanding of human cognition, and to enable the neuroergonomic approach to systems design.

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