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"Adapting C2 to the 21st Century"

Title

Using Physiological Sensors to Understand, Measure and Adapt to Stressors in the C2 Environment

Topics

C2 Metrics and Assessment, Cognitive and Social Issues, C2 Technologies and Systems

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Abstract

Fatigue and workload are always present in command and control centers. Understanding how these factors affect situation awareness and decision making by taking physiological measurements would greatly enhance our ability to evaluate and design command and control systems that optimize cognitive attributes and increase warfighter capabilities in operational and training environments.

The Johns Hopkins University Applied Physics Laboratory (JHU/APL) is establishing a physiologic sensor suite to investigate the relationships between physiological measures captured via non-invasive sensors and a warfighter's performance under conditions of stress (including increased workload) and fatigue. The sensors include an electroencephalogram (EEG); an electrocardiogram (ECG); blood pressure, temperature, and respiratory monitors; a galvanic skin response (GSR) sensor; mobile and stationary eye trackers; and software to integrate the sensor outputs.

One goal for establishing the suite is to develop *objective, non-intrusive* human performance measurement techniques to uncover the relationships between warfighter cognitive state, physiological measures, and warfighter performance. This work will build on previous research by the augmented cognition community and JHU/APL.

This paper provides a background into the discipline of augmented cognition, a description of JHU/APL's sensor suite, a summary of past research related to augmented cognition, and a discussion on planned future activities.

Introduction

External and internal stressors, such as fatigue and workload, are pervasive in modern life, and military life is no exception. Fatigue and workload will always be issues in command and control centers and can significantly affect military operations. They alter warfighters' ability to perceive, understand, and respond to incoming data and information, as well as impact their decision making abilities. This is particularly important as operators must sort and comprehend larger amounts of data and information generated by automated systems. In addition to the increasing risk of data and information overload, operational environments are employing fewer people who are expected to perform at higher levels of efficiency than ever before, increasing the prevalence of fatigue in operational settings.

The need for more quantitative and reliable techniques for assessing the impact that fatigue and workload have on operator situation awareness and performance is critical to effectively evaluating command and control systems for operational effectiveness and impact on warfighter decision making. Such assessment techniques would also enhance the design of new systems that optimize a warfighter's current capabilities and limitations in command and control.

One domain addressing these issues is augmented cognition, which started as a Defense Advanced Research Projects Agency (DARPA) initiative in 2001 led by Navy Commander Dylan Schmorrow. The following sections provide a background on the augmented cognition domain, describe JHU/APL's augmented cognition sensor suite, provide an overview of related research, and describe future experimental aspirations at JHU/APL.

Augmented Cognition Background

Augmented cognition strives to mitigate the limitations and extend (augment) the capabilities of the human mind to greatly increase an operator's ability to perceive, comprehend and understand incoming data and information. Consequently, the discipline incorporates knowledge and techniques from fields such as neuroscience, physiology, cognitive science, computer science, human factors, and information management. The principal concept enabler is the development of technology that adapts the operator's environment to the operator's current mental state, which can change quickly over time due to factors such as stress (from boredom to over-excitement) and fatigue. To achieve this enabler, two broad research areas in augmented cognition have emerged: 1) developing methods to objectively measure an operator's cognitive state and 2) developing methods of altering an operator's environment to account for their current cognitive state.

In the first research area – developing methods to objectively measure an operator's cognitive state – many techniques have been investigated. A wide range of bio-metric sensor technologies have been used with differing results and levels of success. These included, but are not limited to, the use electroencephalograms (EEG) readings of various brain wave activities and electrical impulses, functional Magnetic Resonance Imaging (fMRI) that measures the hemodynamic responses in the brain, functional Near InfraRed (fNIR) which is spectroscopic neuro-imaging, electrocardiogram (ECG) readings of electrical activity in the heart, Galvanic Skin Response (GSR) which measures skin conductivity, and eye tracking. In many cases (Poythress et al., 2006; St. John, Risser, & Kobus, 2006; Tremoulet et al., 2006), data was fused from more than one bio-metric sensor to form a gauged cognitive value. The gauged cognitive values were then used to activate mitigation strategies once a certain threshold was reached.

Fusing data from several heterogeneous bio-metric sensors is difficult, especially when trying to synchronizing those data with operator action. The work performed in the augmented cognition program has laid the foundation and learned many lessons that will benefit future research. One of the greatest lessons learned was that collecting sensitive bio-metric sensor data in uncontrolled environments produces dirty data, that is, data that is wrought with anomalies produced by the external environment and the participant. Brain imagining is extremely sensitive; eye-blinks to vehicle movement can cause erroneous data that must be filtered. Unfortunately, filtering excessive noise from the data may also remove data of interest, thereby, leaving an incomplete data set. In general, better results were acquired by those conducting experiments in a more controlled

environment. A difficult balance must be struck between the sensors' ability to collect accurate data and the sensors' level of invasiveness, comfort, and portability.

In the second research area – developing methods of altering an operator's environment to account for their current cognitive state – the focus was primarily on altering the information content on displays. These alterations are often referred to as mitigation strategies. For example, when a warfighter is perceived to be stressed, the system may only provide the information required for immediate use as opposed to a more comprehensive set of information. Other strategies slow the rate of information presented or give operators decision aides that prioritize their tasks.

A significant amount of work and research remains in the field of augmented cognition. Enormous amounts of data need analyzing. Additionally, determining how best to fuse data from several heterogeneous, bio-metric sensors is unresolved, especially when trying to synchronize the data with operator actions. Furthermore, efforts on how best to collect sensitive bio-metric data are ongoing. Fusing and filtering illustrate just some of the on-going challenges currently facing augmented cognition practitioners.

JHU/APL Physiological Suite

To answer or develop solutions for the remaining and future augmented cognition challenges, JHU/APL has established a physiological sensor suite. The JHU/APL suite consists of sensors from various vendors (Table 1). The decision of which equipment to purchase was based on an evaluation of cost, ease-of-use, reputation, and previous use in the augmented cognition research community. The equipment is currently located in a JHU/APL command and control laboratory, the Precision Engagement Transformation Center (PETC). However, since the equipment is light, portable, and packaged in carrying cases, it can easily be relocated to other research locations.

Two laptops meet the necessary computing requirements for the suite. One laptop is dedicated to the Seeing Machines stationary eye tracker. The other laptop is used as a processing unit for the ASL mobile eye tracker and for the biofeedback package suite developed by Thought Technology.

Table 1 - Sensors in JHU/APL's physiological suite.

Device		Measures (Physiological component)	Equipment	Image
Eye Tracker	Head-Mounted	Gaze, PERCLOS*	Applied Science Laboratories Mobile Eye (Lightweight Tetherless Eye Tracking)	
	Stationary	Gaze, PERCLOS*	Seeing Machines FaceLab 4.0 with Analog Stereo Tracking Cameras	
Skin Response Sensor		Galvanic Skin Response	Thought Technology GSR/TEMP 2X	
Biofeedback Sensor Suite		ECG, Temperature, Respiration, Heart rate/Blood pressure	Thought Technology ProComp Infiniti	
EEG		EEG	Oxford Medilog	

* PERCLOS - PERcent Eye CLOsure; the percentage of eyelid closure over the pupil over time, it reflects slow eyelid closures ("droops") rather than blinks. PERCLOS is often used as a fatigue indicator by capturing the onset and periodicity of micro-sleeps or naps.

Augmented Cognition Related Experience

Assessment of Workload

One notable success in the Augmented Cognition field, which JHU/APL is intimately familiar with, was achieved by Lockheed Martin's Advance Technology Laboratory (LM-ATL). LM-ATL conducted research using the Tactical Tomahawk Weapons Control System as a test platform and trained Navy operators as participants. LM-ATL used EEG, ECG, GSR, and limited eye-tracking data to determine the weapon system operator's cognitive state in terms of mental workload. The EEG, ECG, and GSR data were fused in a Cognitive State Assessor (CSA) that produced an overall indication of the operator's mental workload. The results showed that workload measures determined by bio-metric sensors correlated to more traditional workload measures (e.g., NASA-TLX and Multi-function Information Distribution System (MIDS) workload predictor model) (Tremoulet et al., 2006). This success led to the development and implementation of a mitigation strategy to aid the tomahawk operator when mental workload is high.

The mitigation strategy implemented by LM-ATL was a task manager modification to the graphical user interface. The task manager provided the operator with a list of actions to be performed prioritized by their time criticality. One of the principals of augmented cognition is that the mitigation strategies be dynamic and only available to the operators when they are under certain levels of stress. Therefore, a threshold within the CSA was established. When the threshold was exceeded, the interface presented the task manager. Initial analysis indicated that performance improved when the mitigation strategy was introduced. Although limited, this closed-loop system fulfilled the goal envisioned by DARPA's augmented cognition initiative – to develop systems that understand operators' cognitive states and adapt to enhance their performance.

Assessment of Fatigue

Like workload, fatigue can be measured using physiological sensors and affects warfighter performance. The exact causal relationship between fatigue and performance, however, is difficult to define. While many studies demonstrate that fatigue can impact performance, particularly specific types of performance like psycho-motor, drawing exact correlations between fatigue and performance is challenging. Furthermore, data from the real world shows that humans are very adept at combating or mitigating fatigue, especially when using pharmacological interventions (i.e., drugs, caffeine, nicotine, etc.). Finally, fatigue is very situation-, person-, and task-specific. Thus, applying correlations or relationships of fatigue's affects on performance for one task to another task may be invalid.

To overcome some of these challenges and leverage existing fatigue research, JHU/APL investigated using situation awareness (SA) as an intermediate step to help determine how fatigue affects performance (see Figure 1). Situation awareness (SA) is the understanding of what is happening in the environment, how things are changing, and

what could happen in the future. Internal and external factors, including fatigue, affect SA, which is a critical factor in successful and efficient operator performance.

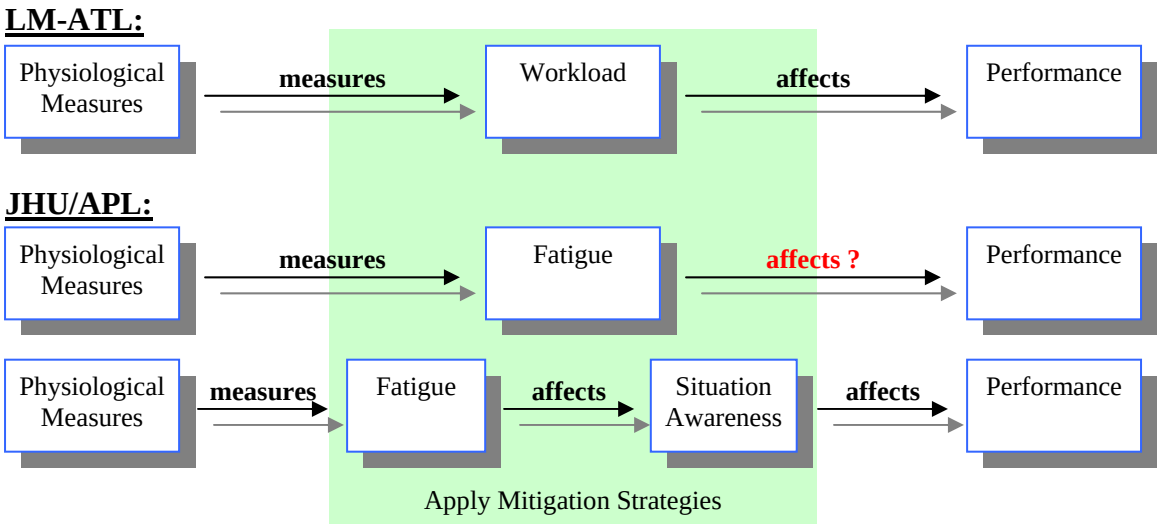

Figure 1 - Human Performance Measurement Activities

During two experiments, JHU/APL investigated the relationship between fatigue and situation awareness (SA) using physiological sensors (McKneely, Bevan, Cropper, Iny, & Vaughan, 2006; Moundalexis, McKneely, & Cropper, 2007). These experiments helped familiarize and train the JHU/APL staff on using physiological sensors and employing JHU/APL's SA assessment method, which is complemented by a real-time metric tool (Provisional Patent 2198-6606). Unlike other SA assessment tools, JHU/APL's tool uses a novel assessment approach to generate a single weighted score per subject per situation. Such a score can now be correlated with other metrics to evaluate relationships and interactions between various factors, like fatigue and performance. While developing this SA assessment method, JHU/APL extended the levels of SA previously defined by Endsley (1995) and added a new level between Endsley's level 2 and level 3 that addresses trend analysis. Trend analysis enables the tracking of changes over time and assists in the prediction of what will happen next. Thus, JHU/APL's SA definition contains 4 levels: perceive, comprehend, assess, and anticipate (see Figure 2).

JHU/APL's SA measurement method starts with the development of probe questions applicable to the operational task of interest. Once developed, these probes are assigned an SA level prior (selected examples from one study are listed in Table 2). Next, subject matter experts (SMEs) are identified to role-play as supervisors. During the experiment, these "supervisors" seek information from participants that would normally be requested in operational scenarios, creating a realistic context in which to deliver the probes and record answers. In addition to collecting responses, the SMEs also judge and record the confidence of participants' responses. At the conclusion of a study, the JHU/APL SA measurement technique uses the accuracy and confidence of each participant's responses

to compute weighted SA scores for various categories, such as overall score, level of SA, and level of command.

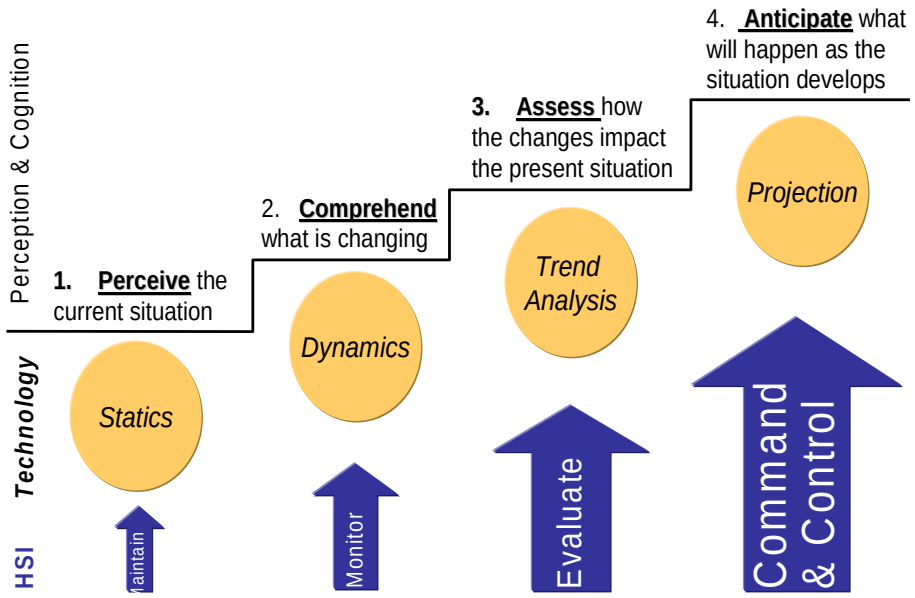

Figure 2 - JHU/APL's Four Level SA Definition (Based on Endsely (2000)).

Table 2 - Sample SA probes with corresponding levels within the Undersea Warfare domain.

Question	SA Level
1. Are there any active contacts?	1
2. What was the last bearing?	1
3. Is the towed array stable?	2
4. Which contacts would you classify as non-sub?	2
5. Are contacts getting weaker?	3
6. What way would you turn to resolve bearing ambiguity?	3
7. What maneuver would you recommend to regain contact?	4
8. Do you predict that target strength will decrease?	4

In one experiment (McKneely et al., 2006), JHU/APL used an eye tracker and ECG as physiological sensors along with the SA assessment method to investigate fatigue's impact on SA in an Undersea Warfare domain. Initially the study sought eight sonar operators; however, due to availability, only four sonar operators between the ages of 18 and 35 already trained on the Improved Performance Sonar (IPS) Passive Acoustic Functional Segment (PAFS) volunteered following a recruitment notice sent via official Navy message traffic.

The participants experienced 36 hours of continued wakefulness in order to simulate chronic fatigue which many sonar operators develop as a result of current shift rotations. At the start of the 36 hour period (approximately three hours after waking) baseline measurements were taken on all systems for each participant. After the participants were

awake for twelve hours, eight test cycles were conducted every three hours. Each test cycle (and baseline) involved completing a series of cognitive tests, subjective surveys, and SA tasks. SA probes were delivered in a realistic manner and participants were instructed to answer as if they were performing this task while underway. While conducting the SA task, participants' faces were analyzed by the eye tracker which measured eye scanning, blinks, and slow eye closure. All testing was conducted in an environment similar to what would be experienced on-board ship during operations (e.g. low level lighting).

Unfortunately, due to the small sample size, statistical analyses were not capable of providing a definitive relationship between fatigue and SA. However, extensive data analysis of the results showed trends between fatigue and SA. Positive correlations emerged between subjective measures of sleepiness and of effort and frustration with the sonar SA task (i.e., as participants reported being sleepier they also reported using more effort on and being frustrated by the sonar SA task). Negative correlations between subjective measures of sleepiness and of the situation awareness attributes arousal, spare capacity, information quantity, and information quality, suggested that as participants became sleepier their attentional resources and their understanding of the situation decreased.

Overall, this study helped JHU/APL refine its SA definition and assessment method, become familiar with a couple of physiological sensors, and demonstrate a potential relationship between fatigue and effective SA. While the goal of demonstrating a clear relationship between fatigue and SA was unsuccessful, the experimental results do suggest the feasibility of using SA as an intermediate step in showing how fatigue, captured by physiological measures impacts performance. This intermediate step also provides another insertion point for mitigation strategies targeting SA, providing additional opportunities to explore the concept of augmented cognition and bio-feedback.

Future Activities

The series of studies in cognitive state and physiological sensors continues. JHU/APL is leveraging significant advances in augmented cognition and internal investments in C2 infrastructure to continue assessing warfighter contribution to mission performance in realistic environments. In doing so, JHU/APL hopes to provide a framework and scientifically sound evaluation methodology for C2 design and development inclusive of human performance considerations.

The next series of studies will use a physiologic (augmented cognition) sensor suite and investigate the relationships between the physiological measures provided by the sensors and a warfighter's performance under various conditions of stress and fatigue. In the first year, three tasks are being executed:

1. Installation of the physiological sensor suite in an existing C2 laboratory environment,
2. Training a team of people on the sensor suite,

3. Demonstration of the sensor suite while participants execute operational C2 center functions.

In the second year, JHU/APL will focus on the development of objective human performance measurement techniques. Integration of these performance relationships into process analysis systems, like JHU/APL's CAOC (Combined Air and Space Operations Center) Performance Assessment System (CPAS) (Case, Koterba, Conrad, Ockerman, & Vanderberry, 2006) will be investigated. The integration of CPAS's process assessment with warfighters' cognitive state assessment will provide a powerful tool for assessing warfighter performance, in near real-time, in both training and real-world operations.

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