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PERSPECTIVES ON AUGMENTED COGNITION IMPLEMENTATION IN MILITARY GROUND VEHICLE CREW STATIONS

Christopher Mikulski[1], Kayla Riegner, PhD[1]

[1] US Army DEVCOM GVSC

ABSTRACT

Military ground vehicles are transitioning from manually operated platforms to highly automated systems, which fundamentally alters the cognitive demands placed on crew members. Rather than reducing workload, automation frequently redistributes it, introducing challenges associated with supervisory monitoring, autonomy mode calibration, and situational awareness. Augmented cognition (AugCog) offers a closed-loop framework in which real-time physiological and behavioral measures of operator cognitive state can be used to dynamically adapt system interfaces and autonomy levels. This paper reviews six nonintrusive sensor modalities suitable for military ground vehicle crew stations: remote photoplethysmography (rPPG), facial thermography, eye tracking and pupillometry, dry-electrode electroencephalography (EEG), Facial Action Coding System (FACS) action unit (AU) analysis, and elastic electrodermal activity (EDA) sensors. A conceptual multimodal crew station integration framework is proposed, and future research directions are outlined.

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1. INTRODUCTION

The modernization of military ground vehicles has introduced autonomy-enabled capabilities related to navigation, threat detection, and mission planning that show potential for enhanced lethality and survivability. These capabilities have, in many cases, transformed the operator's role from direct controller to supervisory monitor. However, this transition introduces its own class of issues [1][2], such as increasing cognitive workload and error susceptibility. For instance, operators must maintain adequate situational awareness (SA) to intervene when automated systems fail, yet the passive monitoring required by high-level automation often degrades the vigilance it demands [3][4]. In military vehicle crew stations, these challenges are compounded by extreme environmental stressors that constrain the operator's mental capacity.

Augmented cognition, which achieved greater attention in military contexts under the Defense advanced Research Projects Agency (DARPA) AugCog program, provides an approach for addressing these challenges. The original vision, as stated by Schmorrow and Kruse, sought to achieve an order-of-magnitude improvement in human-computer interaction by closing the loop between real-time cognitive state estimation and adaptive system behavior [5]. Since its inception, the AugCog concept has matured through multiple phases, expanding from laboratory demonstrations to integrated system prototypes [6][7]. However, its application in military ground vehicle crew stations remains largely unexplored. This paper aims to bridge that gap by reviewing the theoretical and empirical foundations of AugCog, surveying six nonintrusive sensing modalities that can be integrated into constrained ground vehicle crew stations, and by proposing a conceptual framework for integrating multimodal sensor data in military ground vehicles to drive adaptive user interfaces.

2. BACKGROUND

2.1. Early Efforts

By the early 2000s, interest in the study of augmented cognition emerged from the recognition that advances in computational power had far outpaced improvements in human information-processing capacity. Schmorrow and Kruse proposed a program under DARPA's Information Processing Technology Office that would use real-time neurophysiological measures to detect cognitive bottlenecks – i.e., working memory overload, attentional tunneling, or fatigue – to dynamically adapt user interfaces [5]. Through this program, a series of Technical Integration Experiments (TIEs) demonstrated that real-time cognitive state estimation could drive meaningful user interface adaptations (i.e., deferring incoming messages when the load on working memory was high), leading to improvements in task performance [6].

Following DARPA's program, AugCog broadened into other human factors topic areas. Stanney et al. provides a comprehensive review of the field's evolution, noting the expansion from single-sensor laboratory studies to multimodal paradigms [7].

2.2. Theoretical Foundations

The three theoretical frameworks that underpin the AugCog approach in this paper, as applied to military ground vehicle crew stations, are Wickens' Multiple Resource Theory [8], Endsley's three-level SA model [3], and Blascovich's Biopsychosocial Model of Challenge and Threat [9].

MRT suggests that human information processing draws on a set of semi-independent mental resource pools, differentiated by processing stage, sensor modality, processing code, and visual channel. Tasks that compete for the same resource pool interfere with each other and degrade performance, while tasks that draw on differentiated pools can be time-shared more effectively. As such, the MRT model provides a basis for predicting which combinations of vehicle operator tasks will produce mental overload and, consequently, which user interface adaptations are most likely to be effective.

Endsley's model decomposes SA into three levels: perception of relevant elements,

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comprehension of their significance, and projection of future states. In supervised autonomy cases, the primary threat is what Endsley terms the “out-of-the-loop” problem, namely that operators who are not actively controlling a system lose awareness of the system’s state and the environment [1]. This makes timely intervention during automation failures difficult or unlikely. By addressing and detecting declining SA – via gaze dispersion, pupillometry, or EEG patterns – a dynamically adaptive user interface can proactively cue the operator or adjust the level of automation.

Finally, Blascovich’s biopsychosocial model [9] aims to extend MRT and Endsley’s SA model by distinguishing between challenge states (i.e., when perceived resources meet or exceed perceive demands) and threat states (i.e., when demands outstrip resources). Because these states produce distinct cardiovascular signatures (challenge is associated with increased heart rate and decreased peripheral resistance, while threat shows the opposite pattern), user interfaces designed within an AugCog framework cannot monitor whether an operator is cognitively overloaded but whether the overload is likely to degrade performance (threat) or facilitate peak functioning (challenge).

3. Nonintrusive State Estimation

A central challenge for implementing AugCog in operational environments is attaining reliable physiological signals without impeding operator performance. Traditional laboratory methods, such as wet-electrode EEG, finger-clip pulse oximetry, and gel-based skin conductance sensing, are unsuitable for the austere environments that military vehicle crews operate in. Fairclough established a framework for this, defining the design space as one in which real-time psychophysiological data is used to adapt system behavior in a closed loop [10]. The following subsections review six sensing modalities that show promise for nonintrusive measurement in the context of military ground vehicle crew stations.

3.1. Remote Photoplethysmography

Remote photoplethysmography, or rPPG, estimates blood volume pulse signals from video of the face by detecting subtle color variations caused by changes in the amount of light absorbed by bodily tissue. Unlike contact-based pulse oximetry, rPPG requires only an RBG and/or near-infrared camera and light compute resources to process the signals.

Wang et al. provides an analysis of the algorithms underlying rPPG signal extraction, showing that robust heart rate estimation under varying lighting conditions is possible with careful modeling of skin optical properties and motion artifacts [11]. The ratio of low-frequency to high-frequency HRV power (LF/HF ratio) has been used as a marker of sympathovagal balance, with higher ratios associated with increased mental effort and stress [12].

In the ground vehicle domain, several challenges must be addressed. Vehicle vibration introduces motion artifacts into the video signal, and some protective coverings can partially obscure the operator’s face. In the event of lighting variability or in closed-hatch operations where the ambient lighting is low, the use of near-infrared cameras may be used to help mitigate these issues. Recent work on rPPG algorithms suggests acceleration-compensated signal processing provides a promising pathway for attaining acceptable accuracy in harsh and dynamic environments.

3.2. Facial Thermography

Infrared thermography of the face analyzes emitted thermal radiation to produce a spatial temperature map that reflects hemodynamic processes. Because cognitive workload levels and stress modulate activity in the sympathetic nervous system, this in turn alters blood flow to facial regions, producing measurable temperature changes.

The periorbital, nasal, and forehead regions are particularly informative. Jain et al. investigated this relationship, finding that nose tip temperature decreased as mental demand increased [13]. This is consistent with other findings showing the effects of sympathetically mediated vasoconstriction, which redirects blood flow away from peripheral regions during states of elevated arousal and mental effort.

Thermal cameras suitable for crew station integration are available in compact, uncooled microbolometer form factors. However, the thermal environment inside a military ground vehicle presents calibration challenges. Noise from outside factors, such as ambient and crew body temperature, can create a complex background against which facial temperature variations must be discriminated. As such, regular calibration and background subtraction algorithms are needed for reliable measurement.

3.3. Eye Tracking and Pupillometry

Fixation locations, saccade dynamics, blink rate, and scan patterns are well-established indicators of attention allocation and cognitive engagement. Modern eye trackers can be integrated unobtrusively in crew station displays.

Pupillometry, the measurement of pupil diameter changes, adds a complementary dimension. The task-evoked pupillary response (TEPR) is a robust index of mental effort, with pupil dilation scaling monotonically with task difficulty across a wide range of contexts [14]. Joshi et al. demonstrated that pupil diameter fluctuations are tightly coupled to activity in the locus coeruleus, the brainstem nucleus that modulates cortical arousal and attentional regulation [15]. This provides a direct neurophysiological link between pupil dynamics and cognitive state.

Within a military ground vehicle context, real-time gaze and pupil data can serve as inputs to cognitive state estimators that detect attentional narrowing, degradation of SA, or impending overload to drive adaptive user interfaces.

3.4. EEG Headsets and Wearables

EEG is widely considered a gold standard for measuring neural activity directly. Changes in the brain's electrical patterns, particularly in the alpha and theta frequency bands, are well-established indicators of cognitive workload [16]. Historically, EEG has been operationally prohibitive, requiring cumbersome caps, conductive gels, and extensive setup time. However, the recent development of commercial, dry-electrode headsets, such as those by Neurable, Inc., has dramatically lowered the barrier to entry. These headsets are lightweight, modifiable for ruggedization, and can be put on in seconds, making them viable for real-world settings.

3.5. Facial Action Coding System (FACS) and AU Analysis

Developed by Ekman and Friesen, FACS provides an objective, comprehensive method to describe all observable facial muscle movements, known as Action Units (AUs) [17]. Recent advances in computer vision and deep learning allow for the automated extraction of AU presence and intensity from a simple video feed [18]. Preliminary research suggests that the intensity of specific AUs associated with concentration (e.g., AU4: Brow Lowered, AU7: Lid Tightener) correlates with increased mental demand [19]. This approach is highly appealing as it requires only small, easily integrated cameras, posing minimal physical burden on the Soldier.

3.6. Elastic Electrodermal Activity (EDA) Sensors

Elastic Electrodermal Activity (EDA) sensors, typically embedded in flexible textiles, measure skin conductance, a key indicator of sympathetic nervous system activity, stress, and emotional arousal. Using EDA sensors to monitor a driver's physiological state offers several significant benefits for enhancing vehicle safety and driver well-being. These advantages stem from its ability to provide direct insight into the sympathetic nervous system, which is closely linked to stress, arousal, and cognitive function. Studies have looked at whether electrodermal activity (EDA) reflects driver cognitive distraction under varying traffic conditions and adaptive cruise control (ACC) use [20]. This nonintrusive method could provide objective physiological measurements into the driver's state, providing early detection of potential hazards such as drowsiness.

4. MULTIMODAL MEASUREMENT IN A VEHICLE CREW STATION

No single sensing modality provides a complete or fully reliable picture of operator cognitive state. Each modality is susceptible to distinct sources of noise. Multimodal integration improves classification accuracy by combining complementary signals, provides redundancy against single-sensor failure, and enables discrimination among cognitive states (e.g., high workload vs. fatigue vs. high stress) that overlap in their univariate physiological signatures [21].

4.1. Conceptual Crew Station Design

Putting the sensing modalities in Section 3 together, we propose an AugCog-enhanced conceptual crew station that places sensors in three locations. A near-infrared camera array, mounted on the display panel facing the operator, provides rPPG and FACS/AU analysis. A compact uncooled thermal imager, co-located with the other cameras on the display panel, captures facial thermography data. A remote eye tracker is integrated into the primary display bezel, recording gaze position, changes in pupil diameter, and blink metrics. Dry-electrode EEG sensors are embedded in the tactical communications headset. Elastic EDA sensors are integrated as sleeves on the joystick or yoke controller.

This configuration is designed to maximize signal acquisition while minimizing intrusiveness. All sensors operate passively and continuously, requiring no overt behavioral response from the operator.

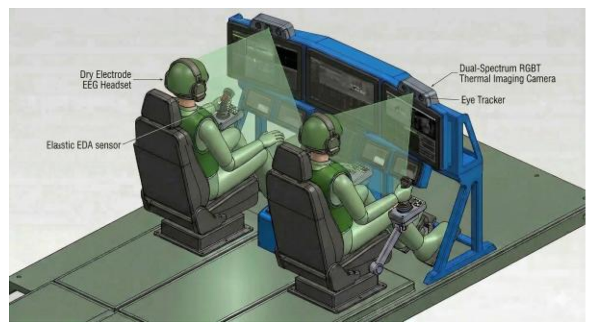

Figure 1. Conceptual Crew Station Design for AugCog Implementation

5. FUTURE WORK AND RESEARCH

Future exploration should include validation studies in operationally relevant tasks such as convoy operations, target engagement, and autonomous supervision. These studies move beyond theoretical or laboratory settings to evaluate capabilities in environments that closely mimic the complexities and pressures of actual missions. The primary goal is to ensure that a given system or strategy will function as intended when deployed.

Future research should also incorporate fusion algorithms for real-time cognitive state estimation. This is a rapidly evolving field, driven by advances in sensor technology and the increasing need for seamless human-robot interaction. This field is rapidly advancing from static, model-based filters toward dynamic, data-driven deep learning solutions. The emphasis is on creating robust, efficient, and increasingly interpretable multimodal fusion algorithms that can reliably estimate cognitive states in complex, real-world environments.

Further work is needed in integration with adaptive autonomy systems for workload sharing and alerting. Adaptive autonomy systems could be adapted for both the user, and the system can initiate changes in the level of automation in real-time. This would transform how humans and machines work together by dynamically adjusting the level of automation to share workloads and provide timely alerts. This flexibility allows for a more fluid and effective collaboration between humans and machines.

Another area to explore is finding a pathway for fieldable prototypes and Army testbed integration. Accelerating the transition from laboratory concepts to fieldable prototypes evaluated by Transformation in Contact (TiC) units would act as live testbeds, integrating, evaluating, and refining emerging technologies in real-world scenarios.

6. CONCLUSIONS

As military ground vehicles evolve from manually operated machines to highly automated platforms, the nature of the crew's job is fundamentally changing. This automation often doesn't decrease the overall mental effort required. Instead, it shifts the crew's responsibilities toward supervisory control, requiring them to monitor the autonomous systems, calibrate their modes, and maintain situational awareness.

To address these new cognitive demands, this paper proposed using an Augmented Cognition (AugCog) framework. This approach creates a feedback loop where the vehicle's systems can adapt to the crew's mental state. By using non-intrusive sensors - such as eye trackers, facial thermography, and dry-electrode EEG sensors - the system can measure the crew's cognitive and physiological status in real time. This data can then be used to adjust the user interface or the level of automation to optimize performance and prevent cognitive overload. A conceptual framework for integrating multimodal measurement in a vehicle crew station was explored. Future research includes validated studies in operational relevant tasks, sensor fusion algorithms for real-time cognitive state estimation, and adaptive interaction protocols.

We argue that Augmented Cognition isn't merely an enhancement; it is a fundamental component for optimizing performance within future intelligent vehicle systems. By dynamically adapting to the operator's cognitive state, AugCog will be instrumental in fostering an integrated human-machine team that is more efficient, resilient, and mission-ready.

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8. CONTACT INFORMATION

Kayla Riegner, PhD
kayla.l.riegner.civ@army.mil

Christopher Mikulski
christopher.m.mikulski@army.mil

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10. ACRONYMS

AU	Action Unit
AugCog	Augmented Cognition
EDA	Elastic Electrodermal Activity
EEG	Electrode electroencephalography
FACS	Facial Action Coding System
GVSC	Ground Vehicle Systems Center
MRT	Multiple Resource Theory
OPFOR	Opposing Force
rPPG	Remote Photoplethysmography
SA	Situational Awareness
TTPs	Tactics, Techniques & Procedures
TiC	Transforming in Contact
TIEs	Technical Integration Experiments