Augmented Cognition Foundations and Future Directions—Enabling "Anyone, Anytime, Anywhere" Applications

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Abstract. Augmented Cognition is distinct from other disciplines due to its focus on using modern neuroscientific tools to determine the 'in real time' cognitive state of an individual and then adapting the human-system interaction to meet a user's information processing needs based on this real-time assessment [1], [7], [14]. Augmented Cognition systems employ the use of physiological- and neurophysiological-driven adaptive automation techniques to mitigate the effects of bottlenecks (e.g., attention, working memory, executive function) and biases in cognition. Being able to non-invasively measure and assess a human-system computing operator's cognitive state in real time and use adaptive automation (mitigation) techniques to modify and enhance their IP capabilities in any application context is a goal that could substantially improve human performance and the way people interact with 21st Century technology [9]. This paper highlights developments in the field of Augmented Cognition most relevant to future Universal Access (UA) applications.

Keywords: Augmented Cognition, human factors, ergonomics, design, neuro-ergonomics, neurotechnologies, neurophysiological, cognitive performance enhancement, training technology, adaptive automation, universal access.

1 Introduction

Augmented Cognition research and development (R&D) is distinct from other disciplines due to its focus on using modern neuroscientific tools to determine the 'in real time' cognitive state of an individual and then adapting the human-system interaction to meet a user's information processing needs based on this real-time assessment [1], [7], [14]. Such 'closed-loop' Augmented Cognition efforts seek to extend a user's abilities via computational technologies that are explicitly designed to address and accommodate bottlenecks (e.g., sensory processing, attention, working memory, executive function), limitations, and biases in cognition, such as limitations in attention, memory, learning, comprehension, decision making, and so forth. The basis of such efforts is grounded in the premise that human information processing

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(HIP) capabilities are a fundamental weak link in establishing a symbiotic relation between humans and computers and in fostering user accessibility [10]. Augmented Cognition systems employ the use of physiological- and neurophysiological-driven adaptive automation techniques to mitigate the effects of HIP bottlenecks and biases in cognition. Being able to non-invasively measure and assess a human-system computing operator's cognitive state in real time and use adaptive automation (mitigation) techniques to modify and enhance their HIP capabilities in any application context is a goal that could substantially improve human performance and the way people interact with 21st Century technology [6], [7], [8], [9], [11].

The following section highlights efforts that various government and academic labs, small and large businesses, and U.S. Science and Technology (S&T) agencies have completed or are currently pursuing in the field of Augmented Cognition. The results of these efforts have been previously presented in various conferences and journals [3], [5], [8], [10], [14] or are in press for forthcoming publications [2], [4], [9], [13], [15], [16], [17] and they represent close collaborations among scientists, developers, and practitioners from multiple disciplines, including: human factors, psychology, experimental psychology, neurobiology, neuroscience, cognitive neuroscience, mathematics, electrical engineering, and computer science. This present summary article, however, aims to present the Universal Access (UA) community with the most relevant highlights of Augmented Cognition efforts regarding research applications and tools (e.g., neurotechnologies) that could be applicable to various UA application domains. Whether the context of the UA application is an operational close-loop system (i.e., closing the loop between assessing cognitive state and initiating real time adaptive changes in the human-system interface), system design and evaluation (e.g., using neurotechnologies to enhance sensitivity and robustness of usability evaluations), education and training (e.g., using neurotechnologies to assess the transition from novice to expert or to adapt a training system in real time to meet a trainee's cognitive needs) or simply entertainment, the Augmented Cognition tools and techniques highlighted here offer the ability to create human-machine synergy and optimization never before realized with UA applications [5], [9], [12], [14], [15].

2 Highlights of Augmented Cognition S&T to Date

Augmented Cognition R&D efforts to date have resulted in a number of validated prototype and operational systems in different military application and training domains; various non-invasive physiological- and neurophysiological-based tools have also resulted [3], [9], [11]. These tools may be used in applications ranging from basic academic research to operational applications and training systems to every day computing and entertainment devices. Further, Augmented Cognition tools and techniques could also be used in the design and evaluation of most any human-system computing device, and thus enable more rapid, effective, and eventually less expensive system design and evaluation processes for such devices. Augmented Cognition R&D efforts from groups such as Boeing, Honeywell Labs, DaimlerChrysler, Lockheed Martin Advanced Technology Laboratories (LMATL), and QinetiQ, each with the aid of various sub-contractors from government, academia, and industry, have demonstrated

Table 1. Summary of Maturing Augmented Cognition Technologies and Proven Implementations to Date (reprinted and adapted with permission [9])

Sensors/Gauges (developed by who)	Use (Measures What / Implemented How)	Appropriateness for Mobile Applications
EDA (Electrodermal Activity)/GSR-based Arousal & Cognitive Workload Gauge (Anthrotronix, Inc.)	*Provides estimates of arousal & general cognitive workload* • Implemented by LMATL in a command & control closed-loop application domain	Most appropriate for stationary users; not yet tested in mobile application domains or with mobile users
EKG (ECG)-based Arousal & Cognitive Workload Gauge (Anthrotronix)	*Uses heart rate variability (HRV) measures to provide estimates of arousal & general cognitive workload* • Implemented by LMATL in a command & control closed-loop application domain	Most appropriate for stationary users; not yet tested in mobile application domains or with mobile users
Body Position/Posture Tracking (University of Pittsburgh)	*Posture shift data, head position, & head velocity are used to gauge levels of attention (i.e., engagement)* • Implemented by LMATL & Boeing in 2 different command & control closed-loop application domains • Implemented by DaimlerChrysler in a vehicular closed-loop application domain	Appropriate for stationary users in stationary or mobile application domains; not yet tested with mobile users & most likely would not be appropriate for such
Stress Gauge (Institute for Human and Machine Cognition [IHMC])	*Uses Video Pupillometry (VOG), High Frequency Electrocardiogram (HFQR ECGS), & Electrodermal Response (EDR) to track autonomic response to time-pressured, high workload tasks & to detect moment-to-moment cognitive stress related to managing multiple competing tasks & is thus good for measuring attention HIP bottleneck effects* • Implemented by Honeywell in closed-loop dismounted soldier application domains	May be appropriate for mobile users & stationary or mobile application domains
Arousal Meter	*Uses interbeat interval (IBI) derived*	May be appropriate

Table 1. (*Continued*)

Gauge (Clemson University)	*from ECG to track decrements in performance due to low arousal states in divided attention & vigilance tasks & is thus a good measure of attention HIP bottleneck effects* • Implemented by Honeywell in closed-loop dismounted soldier application domains • Implemented by Boeing in a command & control closed-loop application domain	for mobile users & stationary or mobile application domains
eXecutive Load Index (XLI Gauge) (Human Bionics, Inc.)	*Uses EEG measures to assess ability to allocate attentional resources during high workload, competing tasks & is thus a good measure of attention HIP bottleneck effects & general cognitive workload* • Implemented by Honeywell in closed-loop dismounted soldier application domains	May be appropriate for mobile users & stationary or mobile application domains
P300 Novelty Detector Gauge (City College New York [CCNY] / Columbia University)	*Uses EEG auditory P300 signals from frontal & parietal electrodes to track attentional resources used to attend to novel stimuli & is thus a good measure of attention HIP bottleneck effects* • Implemented by Honeywell in closed-loop dismounted soldier application domains	May be appropriate for mobile users & stationary or mobile application domains
Engagement Index Gauge (NASA/CCNY/ Honeywell)	*Uses EEG-based measures to track how cognitively engaged a person is in a task (level of alertness) & is effective at assessing attention HIP bottleneck effects associated with both sustained & divided attention tasks, particularly during low workload conditions* • Implemented by Honeywell in closed-loop dismounted soldier application domains	May be appropriate for mobile users & stationary or mobile application domains
New Workload Assessment Monitor (NuWAM) combined EEG, ECG, EOG sensors (Air Force	*Uses combined sensors to gauge general workload levels & estimate executive function & attention HIP bottleneck effects* • Implemented by Boeing in a command & control closed-loop application domain	Most appropriate for stationary users; not yet tested in mobile application domains or with mobile users

Table 1. (*Continued*)

Research Laboratory [AFRL])		
Fast fNIR device (Drexel University)	*Measures brain blood oxygenation & volume changes & is an effective tool for assessing spatial & verbal working memory HIP bottleneck effects* • Implemented by LMATL in a command & control closed-loop application domain	Most appropriate for stationary users but shows promise for mobile users & mobile application domains
Whole Head fNIR (Archinoetics)	*Measures brain blood oxygenation & volume changes & is an effective tool for assessing spatial & verbal working memory HIP bottleneck effects* • Implemented by Boeing in a command & control closed-loop application domain	Most appropriate for stationary users; not yet tested in mobile application domains or with mobile users
Pupillometry (EyeTracking, Inc.'s [ETI] Index of Cognitive Activity [ICA] system)	*Uses proprietary & patented techniques for estimating cognitive activity based on changes in pupil dilation & gaze & is a good measure of general cognitive workload & sensory input, attention & executive function HIP bottleneck effects* • Implemented by LMATL & Boeing in 2 different command & control closed-loop application domains	Most appropriate for stationary users; not yet tested in mobile application domains or with mobile users
Low Density EEG (Advanced Brain Monitoring, Inc.'s [ABM] 3, 6, or 9 channel cap)	*Uses a portable EEG cap, wireless transmitter, & B-Alert software to effectively estimate various types of cognitive states, namely: vigilance/arousal, workload, engagement, distraction/drowsiness, & working memory levels* • Implemented by LMATL in a command & control closed-loop application domain	May be appropriate for mobile users & stationary or mobile application domains
High density EEG (ElectroGeodesics, Inc.'s [EGI] 128 or 256 electrode net)	*Uses an event-related potential (ERP) EEG-based system to estimate which & to what degree particular brain regions are invoked during task performance; may be an effective tool for assessing both verbal & spatial working memory & general cognitive workload*	Appropriate for stationary users; not yet tested in mobile application domains or with mobile users & may be too cumbersome for such applications

Table 1. (*Continued*)

	• Evaluated but not implemented by LMATL in their command & control closed-loop application	
DaimlerChrysler's EEG system (FIRST of Berlin, Germany)	*Uses EEG combined with EOG & electromyography (EMG) to assess low versus high workload levels & is effective at assessing sensory memory bottleneck effects* • Implemented by DaimlerChrysler in a vehicular closed-loop application domain	Appropriate for stationary users in stationary or mobile application domains; not yet tested on mobile users
Event Related Optical System [EROS] (University of Illinois)	*Uses fast optical imaging techniques to identify brain region signatures resulting from cued & non-cued attentional shifts during task performance & thus may be a good estimate of sensory, attention, & executive function HIP bottleneck effects* • Evaluated for potential implemented in Boeing's command & control closed-loop application domain	Appropriate for stationary users in stationary or mobile application domains; not yet tested with mobile users
Cognitive Monitor [CogMon] (QinetiQ)	*Uses behavioral measures from interactions with cockpit controls, EEG-based physiological measures, subjective measures, & contextual information to assess stress, alertness, & various workload levels & is effective at assessing all 4 HIP bottleneck effects* • Implemented in both a military fast-jet simulation & a command & control application environment • Planned for implementation efforts in support of Boeing's AugCog program in their command & control closed-loop application domain	Appropriate for stationary users in stationary or mobile application domains; not yet tested with mobile users

enhanced cognitive performance ranging from 100% to over 500% improvement in HIP targeted bottlenecks (i.e., working memory, executive function, sensory input, and attention) when Augmented Cognition-enabled tools and techniques were implemented. These results were demonstrated with various operational prototypes, such as a U.S. Air Force unmanned aerial vehicle control station, U.S.M.C. smart vehicle system, U.S. Navy fast mover jet simulation, and U.S. Army dismounted-mobile soldier operations) [3], [9], [11]. These advanced closed-loop systems have clearly demonstrated the feasibility, functionality, and practicality of Augmented Cognition-enabled applications and neurotechnologies that have been developed in recent years and continue to be developed by the hundreds of scientists, engineers, and practitioners from diverse yet complimentary, Augmented Cognition-related disciplines.

Table 1 provides a summary of the most promising physiological (e.g., electro-oculography [EOG], heart rate [HR], galvanic skin response [GSR], blood pressure [BP], and pupillometry) and neurophysiological sensor tools currently being used in Augmented Cognition-enabled applications to detect users' cognitive functions in a variety of application domains and environmental conditions [9]. These tools include: stress and arousal meters; engagement indices; portable electroencephalography (EEG), electrocardiography (ECG, EKG), and functional near infrared (fNIR) devices, posture/body state analyses; and pupillometry. The sensors/gauges presented in Table 1 are highlighted because they have been shown to be most sensitive and diagnostic thus far in assessing or inferring cognitive state in real time, while also considering UA relevant requirements (e.g., portability, usability in the field, minimized potential intrusion on user task performance, and potential electromagnetic interference [EMI] during combined sensor/gauge implementation in operational settings). It should be noted that the list in Table 1 is by no means all-inclusive (for a thorough review of available sensors, see NATO report on Operator Functional State Assessment [18]. Furthermore, many of tools highlighted here may be used individually or combined in various ways to assess multiple HIP bottlenecks, as well as other human-system computing and UA task factors (e.g., context, environmental stress effects, individual differences, etc.).

For more detailed discussions of the various applications of the tools presented in Table 1 in a variety of UA-relevant task environments, readers are encouraged to survey the proceedings articles from the first [5] and second [14] Augmented Cognition International (ACI) conferences and the forthcoming publications and conference events highlighted in the next section.

3 Highlights of Forthcoming Augmented Cognition-Relevant Efforts

The contributing authors of the following efforts are playing integral parts in building the foundations and future of the field of Augmented Cognition.

3.1 Aviation, Space, and Environmental Medicine (ASEM) Special Supplement on Operational Applications of Cognitive Performance Enhancement (CPE) Technologies [4]

This ever-increasing rate of Augmented Cognition S&T advancements continues to challenge practitioners of this burgeoning scientific discipline to report, document, and communicate their findings [11]. This special supplement represents one of several forthcoming efforts to capture the essence of the ongoing Augmented Cognition work. It documents existing and emerging achievements in CPE R&D across agencies and institutions. Discussion topics include: operational utility for objectively classifying cognitive state or enhancing cognitive performance during biologically-stressed or increased workload conditions; guidance for the design of CPE technologies that can accommodate such real world cognitive stressors (e.g., sleep deprivation, workload, physical exertion); cognitive metrics and team cognition and performance from both a theoretical and a practical perspective; and considerations for when transferring CPE technology R&D from the lab to the field.

3.2 IEEE Engineering in Medicine and Biology Magazine Special Issue on Optical Imaging of the Intact Human Brain: Physiology, Recording Devices, Methods and Applications [2]

This special issue includes a collection of papers that address the use of optical devices to measure brain activity in humans in non-invasive manners (e.g., via fNIR devices). Although the existence of optical changes accompanying neuronal activity has been known since the 1940's, non-invasive applications to human physiology and cognition are just now emerging and maturing. The latest discoveries and advancements in operational applications of optical imaging R&D are presented.

3.3 Journal of Cognitive Engineering & Decision Making (JCEDM) Special Issue on Augmented Cognition: Past, Present, and Future [13]

This special issue presents: R&D papers in the field of Augmented Cognition, state-of-the-art in associated supporting technologies, and perspectives on future developments and applications. It follows an overarching theme that integrates fundamental research with design and implementation papers. Topics addressed include: integrating real-time physiological sensors into the context of ambulatory tasks; development of real-time physiological sensors that may be more accessible than current EEG and other sensors; effective calibration methods for identifying effective comparison conditions of users (i.e. baselines) to avoid bias in detection of cognitive state changes; establishing a conceptual framework to guide real-time event-based selection of mitigation strategies based on user physiological and behavioral responses; establishing robust architectures to coordinate adaptive automation strategies; and issues of privacy, autonomy, and culpability associated with particular types of embedded (or more *invasive*), Augmented Cognition-enabled technologies.

3.4 Augmented Cognition: A Practitioner's Guide [16]

This book provides an overview of the general approaches to Augmented Cognition R&D that have been adopted to date and describes resulting toolkits that have been developed. This book is meant to be a hands-on guide that provides frameworks and toolkits to guide the efforts of those who aim to become involved in Augmented Cognition R&D or those who simply want to develop a general understanding of Augmented Cognition R&D practices and technologies. It depicts the discoveries and challenges that most any Augmented Cognition researcher, developer, or practitioner may face in our 21st Century human-computing society.

3.5 Foundations of Augmented Cognition, 3rd [12] and 4th [15] Editions

The Foundations of Augmented Cognition series of edited books represents what have become leading references on the field of Augmented Cognition. Similar to the 1st [5] and 2nd [14] editions, the 3rd and 4th editions will bring together a diverse and comprehensive collection of works from international researchers, scientists, engineers, and practitioners working in the field of Augmented Cognition and related fields. Authors contributing to the studies in the 3rd edition will be present their work at the third ACI Conference being held in conjunction with HCI International in Beijing, China in July 2007 (see: www.hcii2007.org); the 4th edition represents studies to be presented at the 4th ACI Conference being held in conjunction with the Human Factors and Ergonomics Society (HFES) 51st Annual Meeting in Baltimore, MD in October 2007 (see www.hfes.org/web/HFESMeetings/07annualmeeting.html).

4 Conclusion

Particular emphasis in this summary article was given to how results and lessons learned from emerging and maturing Augmented Cognition S&T to date may directly impact the future of the UA field via the design of Augmented Cognition-enabled 'anyone, anytime, anywhere' applications. The aggressive goals and objectives required of U.S. government and Department of Defense funded programs [6], [8], [10], [17], [11] have fostered the development of many neurophysiological-based tools and techniques that are maturing enough to become feasible toolsets for HCI researchers, designers, and practitioners in their pursuit of improving human-computer system efficiency and effectiveness and user accessibility [9]. This summary article elucidates the premise that there is a clear link between the fields of Universal Access and Augmented Cognition and that such links should continue to be fostered.

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