Augmented Cognition and Cognitive State Assessment Technology – Near-Term, Mid-Term, and Long-Term Research Objectives

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Abstract. The 1st Augmented Cognition International (ACI) conference was held in July 2005 in conjunction with the HCI International conference in Las Vegas, Nevada. A full day working group session was held during this inaugural ACI conference to facilitate the development of an Augmented Cognition R&D agenda for the near- (1-2 years), medium- (within 5 years) and long-term (> 5 years). Working group attendees included scientists, developers, and practitioners from government, academia, and industry who were invited to participate based on their numerous years of experience and expertise in the Augmented Cognition and related fields. This article highlights key results of the workshop discussions that were focused on Cognitive State Assessment (CSA) R&D objectives, particularly with regard to the design and implementation of CSA tools and techniques.

Keywords: Augmented Cognition, human factors, cognitive state assessment, sensors, design, neuroergonomics, neurotechnologies, neurophysiological.

1 Introduction

In conjunction with the HCI International conference in Las Vegas, Nevada, the Augmented Cognition International (ACI) Society [1] held its first ACI Conference. During this inaugural ACI conference [3], a full day working group session was held to facilitate the development of an Augmented Cognition R&D agenda for the near- (1-2 years), medium- (within 5 years) and long-term (> 5 years). Working group attendees included scientists, developers, and practitioners from government, academia, and industry. Participants were invited based on their numerous years of experience and expertise in the Augmented Cognition and

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related fields. The workshop was focused on three key Augmented Cognition science and technology (S&T) areas: Cognitive State Assessment (CSA), Mitigation Strategies (MS), and Robust Controllers (RC). This article highlights key results that emanated from the portion of the workshop discussions that were focused on CSA S&T research objectives, particularly with regard to the design and implementation of CSA tools and techniques. Future articles will highlight the overall results of the workshop with respect to all three Augmented Cognition S&T areas-- CSA, MS, and RC [8].

During the CSA portion of the workshop, attendees discussed, debated, and agreed upon a final definition of what constitutes a cognitive state sensor—*A cognitive state sensor (or suite of sensors) acquires physiological and behavioral parameter(s) that can be reliably associated with specific cognitive states, which can be measured in <u>real-time</u> while an individual or team of individuals is engaged with a system, where:*

- cognitive state is anything needing to be measured to base design decisions on it;
- cognitive or “functional” state is the moment-to-moment dynamic and functional capabilities (e.g., capacity, bottlenecks) of the human brain, and;
- cognitive or “functional” state has a causative / moderating / predictive relationship to a performance variable.

The following sections highlight the workshop’s findings with regards to the identification of:

- the most important impediments government, academic, and industry scientists and practitioners must overcome in Augmented Cognition CSA research and development;
- the most important challenges to the effective design, use, and adoption of CSA tools and techniques;
- CSA design, development, and implementation successes that have been accomplished to date, and;
- future directions in the design and use of CSA tools and techniques.

2 Key CSA-Focused Results That Emanated from the Workshop

At the heart of Augmented Cognition applications is the ability to capture ‘cognitive state’ or ‘operator functional state’ as a source for driving system adaptation in real time and thus ‘closing the loop’ around the human [1], [2], [3], [4], [5], [6], [9]. Table 1 summarizes CSA technologies that have thus far been explored and successfully implemented by Augmented Cognition researchers and developers via proof-of-concept (e.g., small n, restricted tasks) prototypes of operational applications (e.g., unmanned aerial vehicle control station, smart vehicle system, fast mover jet simulation, and dismounted-mobile soldier operations) [2], [3], [5], [7].

Table 1. Summary of Maturing Augmented Cognition Technologies and Proven Implementations to Date (reprinted and adapted with permission [5])*

Sensors/Gauges (developed by who)	Use (Measures What / Implemented How)	Appropriateness for Mobile Applications
EDA (Electrodermal Activity)/GSR (galvanic skin response)-based Arousal & Cognitive Workload Gauge (Anthrotronix, Inc.)	*Provides estimates of arousal & general cognitive workload* • Implemented by Lockheed Martin Advanced Technology Laboratories (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
Electrocardiography (EKG, ECG)-based Arousal & Cognitive Workload Gauge (Anthrotronix, Inc.)	*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

Table 1. (*continued*)

Arousal Meter Gauge (Clemson University)	*Uses interbeat interval (IBI) derived from ECG to track decrements in performance due to low arousal states in divided attention & vigilance tasks & is thus a good measure of attention human information processing (HIP) bottleneck effects* • Implemented by Honeywell in closed-loop dismounted soldier application domains • Implemented by Boeing in a command & control closed-loop application domain	May be appropriate for mobile users & stationary or mobile application domains
eXecutive Load Index (XLI Gauge) (Human Bionics, Inc.)	*Uses electroencephalography(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	*Uses combined sensors to gauge general workload levels & estimate*	Most appropriate for stationary users; not

Table 1. (*continued*)

(NuWAM) combined EEG, ECG, EOG sensors (Air Force Research Laboratory [AFRL])	*executive function & attention HIP bottleneck effects* • Implemented by Boeing in a command & control closed-loop application domain	yet tested in mobile application domains or with mobile users
Fast functional near infrared (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	*Uses an event-related potential*	Appropriate for

Table 1. (*continued*)

(ElectroGeodesics, Inc.'s [EGI] 128 or 256 electrode net)	*(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* • Evaluated but not implemented by LMATL in their command & control closed-loop application	stationary users; not yet tested in mobile application domains or with mobile users & may be too cumbersome for such applications
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

*Note: The above CSA technology list is by no means all-inclusive. For a thorough review of available sensors, see NATO report on Operator Functional State Assessment [10]. Further, many of these tools may be used individually or combined in various ways to assess multiple HIP bottlenecks, as well as other HCI task factors (e.g., context, environmental stress effects, etc.).

All of the workshop participants were in some way involved with one or more of the R&D efforts to develop and test the operational prototypes. Based on their experiences and lessons learned, the participants reported many varied issues regarding important challenges to the effective *design* of CSA tools and techniques, with a consensus being that basic sensor technology—a critical component of Augmented Cognition applications--will continue to require basic and applied research in many areas, including [5]:

- design of the sensors for ease of use, calibration, appropriate resolution/sensitivity, noise cancellation, and less invasiveness;
- better understanding of neurophysiological, psychological, and cognitive theories that should be driving sensor placement, data analysis, and subsequent ‘cognitive load’ and/or ‘cognitive state’ gauge derivation, and;
- determining appropriate experimental techniques in applied task settings to assess effectiveness of sensors to accommodate both general use settings and individual differences across task domains.

When discussing important challenges to the effective *use* of CSA technology, many of the above issues were reiterated, with additional points of concern being: wearability, ability to account and accommodate for day-to-day and individual user variability, and the development of appropriate signal processing algorithms and their interpretations [5]. Many of these same issues were again noted when discussing important challenges to the effective *adoption* of CSA technology, with additional points of concern including: user acceptance (e.g., ease of use, comfort, safety, trust, control) and fieldability, with value-added performance benefits and objectively measurable return on investments.

2.1 Short-, Medium-, and Long-Term CSA R&D Objectives

The workshop attendees identified the following short-term objectives as future directions to pursue in CSA technology R&D:

- Facilitate collaboration across agencies, institutions, and companies to identify challenges that have been overcome and the variety of approaches that have proven successful / unsuccessful – identify best practices.
- Address calibration issues–can use pure task classification be used or is complex task classification needed?
- How much tolerance to failure there be (e.g., high risk, high pay-off)?
- Need to develop step-wise approaches to the fidelity of CSA validation environments:
  - Identify what is the right/minimal amount of data needed to obtain reliable measures of cognitive state;

  - Consider both central and peripheral physiological measures;
  - Identify which sensors are appropriate for which tasks/ environments (i.e., scalable sensor suites);
  - Consider next generation sensors;
  - Identify potential sensor fusion issues (i.e., conflicting information from sensors) ;
  - Need larger n and more experimentation to enhance reliability, validity, etc.
- How can such technology be implemented with teams of users (e.g., start developing proof-of-concept prototypes)?

The workshop attendees identified the following medium-term objectives as future directions to pursue in CSA technology R&D:

- Identify constraints on sensor technology by exploring the range of operational environments in which it can be feasibly and effectively implemented.
- Explore other domains such as usability testing, system design evaluation, learning/training, entertainment.
- Develop predictive models to complement real-time models; so Augmented Cognition systems can be proactive and not just reactive:
  - will require thorough understanding of task context and how to model too.
- Establish user models to understand issues of fatigue, individual differences and other human variables.
- Develop evaluation approaches that utilize months of data with the same users in efforts to improve classification and model building:
  - enough varied data will facilitate the building of more robust models for each individual;
  - models need to evolve over time (e.g., as person learns, fatigue, etc.)
- Develop tools and techniques that rely on less processing power and time for the analysis/classification of sensor data.
- How can we start validating CSA technology with teams of users?

Regarding long-term CSA R&D objectives, the main consensus was the need to truly operationalize CSA technologies and sensor technology in particular. The continued reduction in analysis/classification of sensor data (e.g., feature reduction) via validated tools and techniques will be needed to ensure CSA and supporting Augmented Cognition technologies are compact and light weight, minimally invasive, and easy to don/doff.

3 Conclusions

This article highlighted some key discoveries and challenges that may impact the future of CSA S&T. The results summarized here may be used as guidance for determining where present and future Augmented Cognition CSA R&D efforts should be focused to ensure the continued growth and maturity of the field and the robustness of its applications. These results may also be used as recommendations and suggested priorities for where national and supra-national institutions (e.g., DARPA, ONR, NIH, NSF) might focus additional funding resources to facilitate the development of new CSA research objectives. Such R&D will be necessary for operational Augmented Cognition S&T to realize its full potential in the near-, medium-, and long-terms.

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