# VIEWS

## PROVOCATIONS

*Augmented cognition research is significantly limited by technological and modeling difficulties.*

# Technology Impedances to Augmented Cognition

**BY M. L. CUMMINGS**

In a recent issue of *Ergonomics in Design* (Summer 2009), there was a debate as to whether systems should be controlled via psychophysiologic operator cognitive state measures (commonly referred to as *augmented cognition*, or AugCog). Griffith was concerned that AugCog systems would circumvent human control, and that AugCog research in general ignored the parallel need to understand how humans could better complement computers. In response, Schmorrow and Stanney, editors of *Augmented Cognition: A Practitioner's Guide* (2008), contended that augmented cognition is primarily about promoting synthesis betweens humans and computers and that psychophysiologic measures are just one focus area of AugCog.

Having recently served on the National Academy of Sciences Committee for Opportunities in Neuroscience for Future Army Applications, I appreciated this debate, but a critical weakness in the AugCog effort not addressed by either side is the "elephant-in-the-room" technology chasm, which includes problems with signal detection and postprocessing algorithms.

Significant uncertainty is inherently present in command-and-control domains, where the bulk of AugCog research has taken place. When environmental uncertainty is coupled with the uncertainty inherent in all psychophysiologic measures and their subsequent analyses, the outcomes of any resultant predictive models are predictions that are so broad that they are not useful, or the predictions carry so much uncertainty they cannot be trusted. In this article, I will discuss these issues in the context of previous AugCog experiments and highlight areas where advancements are needed.

**A Historical View of AugCog Experiments**

Under Defense Advanced Research Projects Agency (DARPA) management, the primary goal of AugCog was to develop "order of magnitude increases in available, net thinking power resulting from linked human-machine dyads [that] will provide such clear information superiority that few rational individuals or organizations would challenge under the consequences of mortality" (Schmorrow & McBride, 2004, p. 129).

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This goal was proposed to occur through the use of neurologic and physiologic measures (e.g., respiration, heart rate, electroencephalography [EEG], functional optical imaging), in conjunction with traditional electromechanical computer input devices (e.g., mouse, joystick). In futuristic operational settings, an operator would wear a headset that would combine EEG, functional optical imaging, eye-tracking, and so on. Through measures generated by this headset, as well as those via galvanic skin response sensors, force feedback in input devices, pressure sensors in seats, and more, the system would enhance an operator's cognitive ability by dynamically controlling the rate, as well as the source, of information.

Proof of concept for the DARPA AugCog program occurred in two phases. In the first phase, researchers attempted to detect changes in cognitive activity in near real time in an operationally relevant setting. In the second phase of this validation process, an operator's cognitive state was manipulated as a result of the measurement technologies developed from the first phase.

For Phase 1, one relatively large experiment/demonstration, the Technical Integration Experiment, was conducted with mixed results (St. John, Kobus, & Morrison, 2003). The objective of the experiment was to determine which psychophysiologic measures could consistently detect changes in cognitive activity for a supervisory control task. Using 20 cognitive state gauges (CSGs) such as EEG, functional near-infrared (fNIR), and body posture measures, as well as input device measures (mouse pressure and mouse clicks), eight subjects completed a series of four simplified aircraft-monitoring and threat response tasks. No CSG was significant across the experiment's three independent variables. Moreover, the only CSGs that demonstrated statistically significant results across two independent variables were mouse clicks and mouse pressure (St. John, Kobus, Morrison, & Schmorrow, 2004), which are indirect indicators of neural or physiologic activity.

A second set of four experiments was conducted to manipulate an operator's cognitive state as a result of near-real-time psychophysiologic measurements (Dorneich, Ververs, Santosh, & Whitlow, 2005). The experiments took place in a video game environment, either at a desktop setting or in a motion capture laboratory. While navigating, participants (16 or fewer) identified friend from foes and monitored and responded to commu-

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nications. A communications scheduler determined operator workload via a cognitive state profile (CSP) and prioritized incoming messages accordingly. The CSP was an amalgamation of signals from cardiac interbeat intervals, heart rate, pupil diameter and microvolt cardiac QRS waveform root mean square amplitude, EEG p300 signal, and EEG power at the frontal (FCZ) and central midline (CPZ) sites.

The authors claimed the CSP produced 100% improvement in message comprehension, 125% improvement in situation awareness, 150% increase in working memory, and increased survivability of over 350%. In addition, the authors claimed, admittedly with anecdotal evidence, that their cognitive state gauges could indicate operator inability to comprehend a message (Dorneich et al., 2005).Unfortunately, there is no clear published account of how the neurologic and physiologic variables were combined to form the CSP, so the ability to independently replicate and verify these results is not possible.

The U.S. Army conducted another related experiment, which focused on developing a mobile cognitive state classification test bed (Dorneich et al., 2007). This EEG-based system was not dry – that is, participants had to wear standard laboratory leads with conducting gel, which were then connected to a laptop computer worn in a backpack. The laptop supported the signal-processing algorithms, the communications scheduler, and other experimental testing elements. Eight participants with no military experience completed a one-hour navigation and communication task with a 35-pound backpack; however, the participant pool was reduced to four for a portion of the experiment. The communications scheduler prioritized messages based on whether the participants were in a low or high task load, showing mission performance improvement from 68% to 96% with cognitive state mitigation.

There were many common significant problems across these studies, and several were acknowledged by the authors (St. John et al., 2004), including issues with construct and external validity (e.g., many highly correlated independent variables), statistical concerns (e.g., low subject numbers, experiment-wise error rates), significant missing data, and a well-known problem inherent in psychophysiologic research: noisy data. Moreover, detecting and then classifying cognitive state changes correctly is extremely difficult, especially in highly dynamic command-and-control settings. Actual combat never adheres to a carefully planned script, and it is questionable whether the kind of limited a priori classification training used in these experiments will have any resemblance to real-world events, thus invalidating the usefulness of such an approach.

The ability to make reliable predictions in real time in a highly dynamic, stochastic setting typical of command-and-control environments is a fundamental obstacle for future AugCog success.

Given the number and severity of confounds for these experiments, the results can be considered preliminary at best. These results do not provide unequivocal scientific evidence that the reported cognitive state gauges can effectively detect change in cognitive activity in a complex human supervisory control task, much less provide accurate recommendations for future actions that can be guaranteed to be at least safe, if not effective.

**Proof-of-Concept Demonstrations Are Not Scientific Proof**

Although these experiments had problematic construct and statistical validity, they provided important information on a number of fronts (i.e., usability, sensor design, areas for algorithm improvement). However, care should be taken when extrapolating results from studies with such serious confounds, especially when making claims of scientific evidence. Moreover, these studies implicitly demonstrate the limitations of AugCog systems, which are rooted squarely in significant technological shortcomings.

The engineering obstacles in combining EEG, fNIR, and eye-tracking devices are substantial. Unless dramatic leaps are made in the miniaturization of these technologies and signal-processing algorithms, the realization of a single headset that can perform all, or even a combination of these technologies, in a mobile environment is more than 20 years in the future. Weight is a critical consideration for dismounted soldiers, and a National Research Council study determined that any new device(s) should not add more than 1 kg to the helmet or 2 kg to the soldier's pack (National Research Council, 1997), which will require an almost eightfold decrease in weight from current technology.

Another major hurdle in the realization of any AugCog implementation will be the development of a wireless EEG device that is unobtrusive, does not require the use of conducting gel, and is able to process on-board signals, all while soldiers are in motion, under often hostile conditions. Some advancements have been made in wireless and dry EEGs, but the signals from these devices are substantially weaker than from the more traditional EEG devices and have fallen under significant scientific scrutiny (Greene, 2007; *Nature, 2007*).

In addition to hardware limitations, the ability to make reliable predictions in real time in a highly dynamic, stochastic setting typical of command-and-control environments is a fundamental obstacle for future AugCog success. The experiments described here were all necessarily simple and artificial, and the communications scheduler made changes in information presentation based on gross differences in perceived cognitive states. The amount of incoming information and large degrees of freedom of possible future states in real settings will mean that much more precision will be needed. Sensors and signal-processing algorithms will have to improve substantially for this to happen, and significant advances are also needed in decision-theoretic modeling. In addition, these models will have to be able to accommodate a significant range of individual variability across an almost limitless set of circumstances.

One final obstacle in achieving the general AugCog goal of enhancing operator performance through psychophysiologic sensing and automation-based reasoning is determining that even if the system could change information streams and incoming information volume for a single individual, how does the system know this change is correct, or even helpful, given the large, highly uncertain state space? This kind of predictive system assumes that it can determine an optimal balance of information for a given operator state. But operator states are inherently linked to the environment, which rarely can be represented in such system models. Before any kind of predictive system could be deployed that controlled inputs to an operator, this system would have to guarantee that it at least did no harm, and it is questionable that, given the current limitations in neuroscience and computer science, this is feasible.

## Conclusion

A clearly stated goal of the AugCog community is to enhance human information-processing capabilities through the design of adaptive interfaces via cognitive state estimation. This work is important and highly relevant today with the U.S. Department of Defense's increasing use of supervisory control systems, particularly unmanned systems. However, although researchers have demonstrated some interesting proofs of concept and made incremental progress in terms of hardware and software advances, the results are preliminary at best. Moreover, they do not suggest that the ultimate desired results are achievable in the near term.

For the general field of augmented cognition to make critical advances, significant focus (and funding) should be placed on hardware development and associated signal-processing efforts. Without critical advances in EEG and other neurologic and physiologic technologies, the AugCog effort cannot make significant progress or be operationalized. Furthermore, significant additional research is needed in the development of decision-theoretic models and predictive algorithms in dynamic, highly uncertain domains for open-loop systems with noisy sensor data.

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