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# CLOSING THE LOOP OF AN ADAPTIVE SYSTEM WITH COGNITIVE STATE

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This paper describes an adaptive system that "closes the loop" by utilizing a real-time, directly sensed measure of cognitive state of the human operator. The Honeywell Augmented Cognition team has developed a Closed Loop Integrated Prototype (CLIP) of a Communications Scheduler, for application to the U.S. Army's Future Force Warrior (FFW) program. It is expected that in a highly networked environment the sheer magnitude of communication traffic could overwhelm the individual soldier. The CLIP exploits real-time neurophysiological and physiological measurements of the human operator in order to create a cognitive state profile, which is used to augment the work environment to improve human-automation joint performance. An experiment showed that the Communications Scheduler enabled higher situation awareness and message comprehension in high workload conditions. Based solely on cognitive state, the system inferred a subject's message comprehension and repeated unattended messages in the majority of cases, without yielding an unacceptably high false alarm rate.

## INTRODUCTION

The U.S. Army is currently defining the roles of the 2010-era Future Force Warrior (FFW). The FFW program seeks to push information exchange requirements to the lowest levels and posits that with enhanced capabilities a squad can cover the battlefield in the same way that a platoon now does. Among other capabilities, the application of a full range of netted communications and collaborative situational awareness will afford the FFW unparalleled knowledge and expand the effect of the Future Force three dimensionally.

Task analysis interviews with existing military operations identified factors that negatively impact communications efficacy. In one example, in the first few minutes of any intense mission, radio communications are a suboptimal method of communications because everybody is intensely focused on their tasks at hand. In one famous raid, for example, the commander did not hear the radio communications informing him that the plan had changed until he was physically grabbed by the ground force commander and given this critical information. The commander responded by radioing his own troops, who also did not respond. The implications of these kinds of situations are many, but, first and foremost, mission critical information must be reliably communicated. What aspects of the communication method can be altered to improve the chances that a message will be received and understood? Does it require a multi-modal, physical alert? Should communications be limited to only critical messages during high workload situations?

An approach was adopted that considers the joint human-computer system when identifying bottlenecks to improve system performance. Key cognitive bottlenecks constrain information flow and the performance of decision-making, especially under stress. From an information-processing perspective, there is a limited amount of resources that can be applied to processing incoming information due to cognitive bottlenecks (Broadbent, 1958; Treisman, 1964; Kahneman, 1973; Pashler, 1994). The DARPA Augmented Cognition program identifies four key cognitive challenges related to different components of information processing: 1) the sensory input bottleneck, 2) the attention bottleneck, 3) the working memory bottleneck, and 4) the executive function bottleneck (Raley, et al., in press). The Honeywell team, sponsored by the DARPA Augmented Cognition Program, is focusing primarily on the Attention Bottleneck. There are many varieties of attention that need to be considered to optimize their distribution (Parasuraman & Davies, 1984): executive attention, divided attention, focused attention (both selective visual attention and selective auditory attention), and sustained attention. Breakdowns in attention leads to multiple problems: failure to notice an event in the environment, failure to distribute attention across a space, failure to switch attention to highest priority information, or failure to monitor events over a sustained period of time.

The appropriate allocation of attention is important to FFW because it directly affects two cornerstone technology thrusts within the FFW program: netted communications and collaborative situation awareness. The Honeywell team has developed a set of cognitive gauges based on real-time neurophysiological and physiological measurements of the human operator. The capability to assess cognitive state to determine allocation of attention provides the opportunity to adapt the soldier's current task environment. Cognitive assessment can drive adaptive strategies to mitigate the specific information processing bottlenecks.

Adaptive automation can either provide adaptive aiding, which makes a certain component of a task simpler, or can provide adaptive task allocation, which shifts an entire task from a larger multitask context to automation (Parasuraman, Mouloua, & Hilburn, 1999). Currently, adaptive systems derive their inferences about the cognitive state of the operator from mental models, performance on the task, or from external factors related directly to the task environment (Wickens & Hollands, 2000). For example, Scott (1999) used the projected time until impact as an external condition to infer that the pilot's attention was incapacitated, at which point the system would perform the "fly up" evasive maneuver to avoid a ground collision. In that case, the automation took over control of the system (i.e., the aircraft) from the pilot.

Adaptive mitigation strategies can include task management, optimizing information presentation via modality management, task sharing, and task loading. For instance, in task management, mitigation strategies might include intelligent interruption to improve limited working memory, attention management to improve focus during complex tasks, or cued memory retrieval to improve situational awareness and context recovery. For example, an air traffic controller might be presented with decision aids for conflict detection and resolution by the automated system when it detects a rapid increase in traffic density or complexity (Hilburn, Jorna, Byrne & Parasuraman, 1997). Modality management mitigation strategies might include utilizing available resources (i.e., audio, visual) to increase information throughput. Task offloading and task sharing to automation are also mitigation strategies to reduce workload. Ultimately, the goals of adaptive automation are similar to those of automation in general, such as avoiding “operator out of the loop” conflicts or mistrust in the automation.

This research has developed a Communications Scheduler to mitigate the attention bottleneck via task-based management and modality-appropriate information presentation strategies. Of particular importance is the soldier’s ability to handle continuous inflow of netted communications and directing his or her attention to the highest priority task to complete his/her mission in this highly dynamic environment. This is crucial to not only his/her own survival but that of his/her fellow soldiers. This paper will address the following questions: does the mitigation strategy imposed by the Communications Scheduler effectively alter the soldier’s cognitive/attentional state? Will the soldier with augmented capabilities show enhanced performance compared with a soldier without the augmented system? The next section will briefly describe the cognitive gauges and the Communications Scheduler.

## System Description

The Honeywell AugCog team has developed a comprehensive suite of sensors (including EEG, pupilometry, physiological measures such as EDR, and ECG) that compose a set of “cognitive gauges.” These include an engagement index, a stress gauge, an arousal meter, an executive load index, and a P300-driven novelty gauge. When the gauges register an overload in the soldier’s cognitive state, the Communications Scheduler employs adaptive automation strategies to mitigate the cognitively intensive role of directing one’s attention to the highest priority items until workload is alleviated.

While the focus of this paper is the development and evaluation of the adaptive strategies employed by the Communications Scheduler, a brief description of the cognitive gauges driving system behavior is in order.

*Engagement Gauge.* The engagement index is a ratio of EEG power bands (beta/(alpha + theta)). The engagement index, as described by Freeman et al. (1999) is a measurement of how cognitively engaged a person is in a task, or their level of alertness. Adaptive systems have used this index to drive control of the automation between manual to automatic modes. In fact, the index has been used to successfully control an automation system for tracking performance and a vigilance task (Freeman et al., 1999; Mikulka, Scerbo, & Freeman, 2002; Pope, Bogart, & Bartolome, 1995).

Consistent with Freeman et al.’s work, EEG data is recorded from sites Cz, Pz, P3, and P4 with a ground site midway between Fpz and Fz. The Engagement Index (beta/(alpha + theta)) is calculated from a running average of powers for different EEG frequency bands (Prinzel, et al., 1999). Prinzel, et al., (1999) reported that adaptive task allocation may be best reserved for the endpoints of the task engagement continuum. Therefore, two levels of engagement (low, high) were measured in this study. The engagement index reflects the selection and focus on some aspect at the expense of the other competing demands, thus it is a measure of focused attention. High levels of engagement reflect selection and attentional focus whereas lower levels of engagement indicate that the subject is not actively engaged with some aspect of the environment.

*Stress Gauge.* The Institute of Human and Machine Cognition developed a composite *Stress Gauge* (Raj et al., 2003; Kass et al., 2003). The gauge uses a weighted average of the four inputs (Video Pupilometry (VOG), High Frequency Electrocardiogram (HFQRS ECG), Electrodermal Response (EDR), and Electromyogram (EMG) from the left trapezius muscle to detect the subject’s response to changes in cognitive load within the virtual environment. The gauge was used to detect cognitive stress related to managing multiple competing tasks on a moment-to-moment basis.

*Arousal Gauge*. Clemson University’s *Arousal Meter* (Hoover & Muth, 2003) derives autonomic arousal from the cardiac inter-beat interval (IBI) derived from the Electrocardiogram (ECG) at one ms accuracy. A three lead ECG is used to detect R-spikes and derive ms resolution IBIs that are then re-sampled at 4 Hz. A fast Fourier transform (FFT) is computed for 16 s, 32 s, or 64 s worth of IBIs. A sliding window is established such that a new FFT is computed every .25 s. When the FFT is computed, the high frequency peak (max power between 9 and 30 cycles per minute) is identified and the power at that peak, termed respiratory sinus arrhythmia (RSA), is stored. Once one minute’s worth of FFT results are stored, the arousal meter begins to generate a standardized arousal which is computed every 0.25 s using a z-log-normal score standardization and the running mean and standard deviation of the RSA values. The gauge has 3 levels (low, medium and high). Increases in this score are associated with increased autonomic arousal and decreases with decreased autonomic arousal.

*Executive Load Gauge.* Human Bionics developed a gauge called the *eXecutive Load Index (XLI)* (DuRousseau, 2004, 2004b) to measure cognitive state. It operates by measuring power in the EEG at frontal (FCZ) and central midline (CPZ) sites. The algorithm uses a weighted ratio of delta + theta/alpha bands calculated during a moving 2-second window. The current reading is compared to the previous 20-second running average to determine if the executive load is increasing, decreasing or staying the same. The index was designed to measure real-time changes in cognitive load related to the processing of messages. This gauge was previously validated to discern trial difficulty in a continuous performance high-order cognitive task battery.

*P300 Novelty Detector Gauge*. The EEG Auditory P300 reflects a central nervous system response to behaviorally relevant infrequent sounds. Previous literature (Wickens, Heffley, Kramer, & Donchin, 1980) suggests that P300 amplitude in response to a task relevant infrequent auditory stimulus is modulated by attentional resources: if the subject is very focused on a primary task the auditory stimulus will be missed and the corresponding P300 diminished. Columbia University and the City College of New York have created a gauge called the *P300-novelty detector gauge (*Sjada, Gerson, & Parra, 2003), that spatially integrates signals from sensors distributed across the scalp, learning a high dimensional hyperplane for discriminating between task relevant (incoming message auditory alert) and task irrelevant responses. In the current task environment a tone is played before an auditory message to evoke a P300 activity. Mitigation strategies are based on the assumption that the presence of a strong evoked response indicates that subjects have sufficient attentional resources to process the incoming message. The gauge includes frontal and parietal electrodes

### Communications Scheduler

The Communications Scheduler mitigates the attention bottleneck via task scheduling and modality management of incoming communications. The system is tasked with determining when and how information is displayed to the soldier. The Communications Scheduler schedules and presents messages to the soldier based on the cognitive state profile, the message characteristics, and the current context (tasks). Based on these inputs, the Communications Scheduler can pass through messages immediately, defer and schedule non-relevant or lower priority messages, escalate higher priority messages that were not attended to, divert attention to incoming higher-priority messages, change the modality of message presentation, or delete expired or obsolete messages.

Messages are characterized by priority (low, medium, or high). The Communications Scheduler looks at three gauges before a message is presented: Engagement, Arousal, and Stress. Each gauge can have a value of High, Medium, Low, or Unknown. Based on the combination of gauges, the Communications Scheduler can perform one of four actions when deciding how to first present the message:

- Present the message immediately in the audio modality with the appropriate "normal" tone proceeding it.
- Present the message immediately in the audio modality preceded by the appropriate "higher saliency" tone.
- Present the message immediately in the text modality.
- Defer the message for presentation after the mission is complete.

After a message has been presented, the Communications Scheduler looks at the XLI and P300 Novelty Detector gauges to determine if the subject had the attentional resources at the moment of message presentation to properly attend to and understand the message. Based on the combination of the two "after" gauges, it can perform one of four actions:

- Replay the message immediately in the audio modality preceded by the same tone used previously.
- Replay the message immediately in the audio modality preceded by a higher, more salient tone than used previously. Note if the first presentation was of the "higher" tone, this replay would use the "highest" tone.
- Do nothing as the gauges have sensed that the subject comprehended the message.
- Not Applicable – the "before" decision precludes any need to make an "after" decision.

## METHOD

An empirical Concept Validation Experiment (CVE) was conducted to assess the performance improvement of a Communications Scheduler driven by cognitive gauges.

### Operational Scenario

The CVE is focused on three critical task elements of the "Raid on Objective" mission, specifically "Navigate to Objective," "Identify Friend or Foe" and "Communications Management." A virtual environment was created using a video game format that included enemy forces, friendly forces, and an urban environment to navigate. The participant is a platoon leader, whose goals were to lead the platoon through a hostile urban environment to the objective, while being careful to shoot enemy soldiers and not shoot members of his own team. Participants also received incoming communications throughout the scenarios, with some messages requiring a response. Participants received status updates, mission updates, requests for information, and reports; these incoming communications are a primary source of their situation awareness.

A reward metric was incorporated to encourage participants to perform all three tasks to the best of their ability throughout each scenario. Their goal was to navigate to the objective as quickly as possible, but they also had to minimize the number of times they were shot and had to respond appropriately to messages. Participants who balanced these tasks throughout scenarios could receive an additional $3 per scenario. Their performance results were displayed for them at the end of each scenario so they would know how they were doing.

### Research Objectives

*Research Questions*. The goals of the experiment were focused on assessing the ability of the gauges to drive mitigation strategies and whether the mitigation strategies will enhance performance. Research questions included: Will the integrated gauges be sensitive enough to detect a change in the participant's cognitive state? Will cognitive state changes correlate with changes in the participant's tasks? Will the mitigation strategy imposed by the Communications Scheduler effectively alter the participant's cognitive/attentional state? Will the use of the communications scheduler enhance the participant's overall performance as compared to performance without the augmented system? This paper focuses on the final two questions.

*Hypothesis*. The CVE hypothesis states the "smart" message scheduler will enhance overall performance on the Managing Communications task (as measured by message response and situation awareness metrics), while not significantly degrading performance on the Navigation to Objective and Identify Friend or Foe tasks. Specifically, under augmentation, it is hypothesized that subjects will have better situation awareness for message content and subjects will attend better to high and medium priority messages.

### Experimental Design

*Independent Variables***.** The study is a 2 (Workload: high, low) x 4 (Route: 1, 2, 3, 4) x 2 (Augmentation: on or off) within-subjects repeated measures design, partially counterbalanced for independent variable presentation (Augmentation). Participants were randomly assigned to see either the augmentation on or augmentation off scenarios first.

*Participants***.** The CVE had 12 male participants with a mean age of 24 years (range = 18-30). All participants had normal or corrected-to-normal vision, normal hearing and moderate experience playing first-person shooter games. Participants with some game playing experience were preferred to reduce learning effects that could be associated with practice while using the virtual environment. Participants were paid for their participation, and could earn a bonus in every scenario for successfully balancing the three tasks.

*Dependent Variables***.** Scenarios differed in workload (high, low) and in augmentation (on/off). For the augmentation variable, there were a set of metrics for each of the three principle tasks. For the "Navigate to Objective" task, the goal of augmentation was to do no harm. In other words, use of augmentation would not degrade performance on metrics such as total run time, evasiveness, and total number of times a subject is hit by enemy (OPFOR) fire. Likewise, for the "Identify Friend or Foe" task, augmentation should do no harm to metrics such as hit rate, miss rate, total number of times a subject hit friendly forces, and reaction time to enemies coming into view. For the "Manage Communications" task, the Communications Scheduler is designed to improve subject performance in metrics such as the percent of messages to which subjects correctly responded, and the percentage of situation awareness probes correctly answered.

Workload was also measured using the NASA TLX to document the participants' perceptions of the workload for each block of four scenarios. For these metrics we expected to see that the high workload scenarios would differ significantly from the low workload versions of the scenarios.

## RESULTS

### Performance Analysis

*Workload*. For seven of the nine metrics listed above, workload was significant in the expected direction. The low workload scenarios differed significantly from the high workload scenarios. For instance, in the high workload scenarios, participants took more time to complete the tasks, they were shot more often by the enemy, and they exhibited more evasive behavior than they did in the low workload conditions. Participants rated the high workload situations significantly more mentally ($p < .005$), physically ($p < .02$), and temporally ($p < .005$) demanding, as well as more frustrating ($p < .03$) using the NASA TLX scales.

*Augmentation: Navigate to Objective.* The goal was to not have augmented conditions contribute to performance decrements in navigation. There was no significant effect of augmentation on evasiveness or the number of times the participant was shot by the enemy. There was a significant effect of augmentation on time to navigate to the objective ($p < .01$), where participants took longer to navigate to the objective in the augmented condition. In the augmented conditions, the warning tones associated with messages sometimes prompted participants to pause and wait for the incoming message, resulting in longer run times. In this case, although longer run times occurred, the augmentation encouraged participants to adopt strategies for managing the multiple tasks in the scenario.

*Augmentation: Identify Friend or Foe.* The goal was to not have augmented conditions reduce performance in the identification of friends and foes. There was a marginally significant ($p<.10$) increase in the time it took for participants to react to friends and foes when augmentation was on. The communications scheduler slowed reaction times, but significantly improved the hit rate ($p < .05$) and lowered the miss rate in high workload scenarios. This indicates that participants were able to take the time to judge whether a friend or foe had appeared in the scenario, thus improving their ability to shoot enemies and refrain from shooting their comrades.

*Augmentation: Manage Communications.* The goal was for augmentation to improve participants' responses (i.e., correctly acknowledge a message) to messages and improve their awareness of message content (i.e., correctly answer situation awareness probes at the end of the scenario). There was a significant effect of augmentation in the high workload scenarios only ($p < .02$) for situation awareness to message content. Participants better understood the nature of communications and how they pertained to the scenario when augmentation was on. There was a trend in the expected direction indicating more messages were correctly responded to in both high and low workload scenarios ($p = .14$) when augmentation was on.

Overall, there are several indications that augmentation benefited participants in this study. Under high workload conditions, the communications scheduler produced better situation awareness and improved the ability of participants to correctly identify and shoot the foes. These results are consistent with many program findings (e.g., Prinzel et al., 2003) that show the benefit of augmentation at the extreme ends of the workload space.

### Mitigation Analysis

Analysis of the success or failure of the Communications Scheduler can be determined by examining how the augmentation behaved in relation to the incoming messages that required a response. Approximately 70% of the messages required an overt response from the subject in the form of an acknowledgment (i.e., said "Acknowledge") that they heard *and* understood the message, or required the participant to answer with information from either a previous message or from information available in the scenario. For these messages, the experimenter recorded if a participant responded appropriately. In addition, if a message was repeated, the participant had another opportunity to respond. Participants acknowledged the first presentation of a message 72.5% of the time. In cases where the participant failed to respond appropriately the first time, the message was repeated 71.6% of the time, with a follow-up acknowledgment rate of 95%. In cases where participants acknowledged the first presentation of a message, messages were repeated only 23.7% of the time. These latter results indicate that either the participants were responding incorrectly or without comprehending the message, and therefore a repetition of the message was warranted or the scheduler misinterpreted the cognitive state of the participant.

## DISCUSSION

With the aid of our proposed adaptive system we aim to decrease the soldier's risk by improving their ability to comprehend and act on available information. The mitigation strategies were designed to improve performance on the Manage Communications task while not decrementing performance on the Navigate to Objective and IFF tasks. Overall, the CVE results showed some promising findings for the communications scheduler as seen from the results described above. In particular, the analysis of the behavior of the system with regards to subject acknowledgement and comprehension of messages was compelling. Based on cognitive state, the system was able to infer a subject's message comprehension and repeat unattended messages in the majority (71.6%) of cases, with a false alarm rate (23.7%) that can be partially attributed to the subjects' automatic acknowledgment of a truly unattended message. It is important to remember that these mitigations were driven solely by the cognitive state of the subject, as measures in real time by five "cognitive gauges." Thus, the CVE has shown a concrete example of "closing the loop" with an adaptive system that uses physiological and neurophysiological sensor inputs.

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