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REVIEW ARTICLE

CLOSING THE LOOP BETWEEN MAN AND MACHINE: MITIGATING HAZARDOUS STATES OF AWARENESS WITH ADAPTIVE AUTOMATION

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Background: The past century of passenger flight has seen continuous improvement in aviation safety by aerospace industry and the research community. However, while commercial aviation accident rates have continued to decline, human error-related incident and accident rates remain remarkably constant across all types of aviation. Unfortunately, this level of human error is unacceptable when considering projections for increased traffic volume, and is likely to yield more incidents and accidents unless a more complete understanding of operator error is achieved and remediations are implemented. One area of interest highlighted by researchers is Hazardous States of Awareness (HSAs) that can result from deficiencies in the design and inappropriate use of human-machine interfaces. Identifying and mitigating HSAs is critical for reducing operator errors. One promising approach uses psychophysiological measures which enable automated systems to adapt to the operator's state and modify modes of operation to support optimal human performance. This paper will survey previous research and describe future directions for the application of psychophysiological measures of operators derived from cortical and autonomic assessment to perform real-time adaptive modulation of human-automation interactions.

Keywords: Hazardous States of Awareness, human error

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HUMAN ERROR IN AVIATION INCIDENTS AND ACCIDENTS

A major challenge for civil aviation safety organizations, such as the National Aeronautics and Space Administration (NASA) and the Federal Aviation Administration (FAA) is to improve the safety record of an industry with an already exceptionally high level of safety. There have been substantial improvements in aviation safety made during the past century of passenger flight due to the aerospace industry's success at developing increasingly advanced and robust technology [7]. A closer look at the causes of aviation accidents reveals that human error accounts for greater than 70% of incidents and accidents in air carrier, commuter air transport, and general aviation operations [6,40,44]. While commercial aviation accident rates have continued to decline, the proportion of human error-related incidents and accidents remains remarkably constant; consequently some have questioned whether the current accident rate is as good as it gets [40]. Further, this consistency is unacceptable when considering projections for increasing traffic volume [8], which will probabilistically lead to more incidents and accidents unless a more complete understanding of operator error is achieved and improved operations are implemented.

The role of human error in incidents and accidents is explicable considering the responsibilities of aircrew during flight: constant awareness of the current state of the aircraft in three-dimensional space and as it changes over time and the environment (air traffic, weather information, and terrain). Also, if a fault occurs at any level of the system (an aircraft component fails), the aircrew must compensate for this failure whether or not functionality is restored. The importance of human operators and their ability to flexibly respond to changing demands of tasks and hazards in complex human-machine aviation systems has been the focus of aviation psychology [9]. Researchers noted that it was overly simplistic, if not naive to write off the causes of accidents to operator error [14]. The term "human error" is deceptive, as it implies that the human was the sole cause of the incident or accident. Human error may be observed because a human was the last line of defense in a series of failed system elements. Conventional accident analyses focus almost exclusively on the actions of workers at the front lines; for aviation, the pilots, co-pilots, flight engineers, air traffic controllers, and dispatch operators. Insightful researchers of human error in aviation [18] suggested a broader approach, which considers that accidents and incidents emerge from a confluence of system failures – including individual human performance. The theoretical Swiss Cheese model [30] and the Human Factors Analysis and Classification System (HFACS) [41] reveal issues operators encounter when interfacing with complex systems that researchers and system designers can systematically examine to improve operator performance and safety.

HAZARDOUS STATES OF AWARENESS IN AVIATION

A major component of human error in operational incidents and accidents stem from human conditions that have been termed "hazardous states of awareness" (HSAs) [24]. HSAs typically occur when operators of human-machine systems perform prolonged, routine, and habitual activities. A taxonomy of HSAs has been developed to further understand types of HSAs and encourage systematic study of countermeasures [36]. Since the pilot is the last line of defense in an aviation context, efforts to understand and characterize HSAs for the purpose of decreasing human error represent an area for continued improvement in aviation safety. Human error in aviation has been dealt with principally by automating flight tasks. Although effective to the degree that this automation is reliable, it relegates the pilot to the role of backup to or cross-checker of automation [22,37,39]. This results in additional problems (e.g., complacency, inattention, etc.) noted by pilots and researchers [1]. Such issues instigated "human-centered" automation concepts, which aim to improve pilot-automation interaction, and maintain an active role for the pilot. One such concept, *adaptive automation* (AA), permits flexible allocation of automation functions based on consideration of factors including operator state [34]. Some uses of adaptive automation have shown benefits in performance, increased situational awareness, and decreased cognitive workload in human-machine system users [29]. Adaptive automation is a nascent and challenging area of research; now is an exciting time to be investigating this capability.

PSYCHOPHYSIOLOGICALLY ADAPTIVE SYSTEMS (PAS): AA AS A SPECIAL CASE OF A CLOSED-LOOP SYSTEM

Researchers at NASA Langley Research Center established the first program to assess pilot mental state, specifically task engagement, via psychophysiological measures: electroencephalogram, event-related potentials, and heart-rate variability (EEG, ERP, and HRV) in the early 1980s [27]. The early work done by this group and research sponsored by this group transitioned basic psychophysiological research techniques to more applied/operational settings [3,4,45]. A major impetus for this research effort came through an analysis of narratives in the Aviation Safety Reporting System (ASRS), which identified suboptimal awareness states: complacency, boredom, diminished alertness, compromised vigilance, and lapsing attention. This analysis led Pope and Bogart [24] to identify hazardous states of awareness and investigate specific psychophysiological markers of operator engagement. This approach presented a promising technique for identifying diminished functional state. Pope and Bogart [23] extended this work by focusing on modification of attention in individuals diagnosed with attention-deficit disorder. The adaptive system was programmed to recognize each individual's characteristic EEG profile, using a technique similar to that used by Pope and Bogart [24].

Science fiction is an influential source and has been identified as contributing to real-world technology, war, and politics [42]. Looking ahead to the future and considering the possibilities of blending human and machine potential, U.S. Air Force researchers described a prospective aviation technology a symbionic cockpit capable of considering the mental state of the pilot to optimize mission performance [31]. Inspired by these researchers and a description of a Physiological Control and Monitoring System (PCMS) from science fiction of two decades earlier [28] and informed by work in the fields of psychophysiology and biofeedback, a closed-loop biocybernetic system was developed and experimental results from this system demonstrated the operation of a psychophysiologically adaptive automation system [26]. The biocybernetic system was based upon a closed-loop concept that involved adjusting or modulating (cybernetic, for governing) a person's task environment based upon a comparison of that person's psychophysiological responses (bio-) with a training or performance criterion.

This effort to construct a *biocybernetic* system benefited from a fortuitous confluence of developments and available capabilities. A shift in emphasis within the aerospace human factors community from the problems of high workload to concerns about underload issues from increasing automation, articulated by Hancock and colleagues [12,13] and others [11,16], resulted in a focus of the NASA Langley Research Center (LaRC) mental state research onto issues of complacency and boredom. The Multiple-Attribute Task (MAT) Battery, developed at LaRC [2] provided a set of integrated laboratory tasks resembling activities performed by pilots including compensatory tracking, system monitoring, resource management, and com-

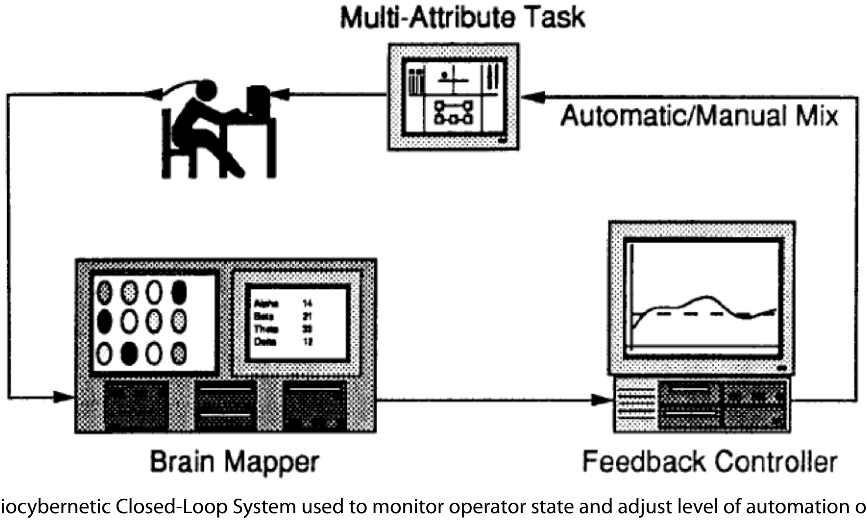

Fig. 1. Biocybernetic Closed-Loop System used to monitor operator state and adjust level of automation of the Multi-Attribute Task Battery. (modified from [26])

munication tasks. The subjects in experiments could be asked to perform the tasks individually or simultaneously and the tracking task could operate in automatic or manual mode while the other tasks were designed to operate in manual mode. The MAT Battery was not designed to be a flight simulator; the great utility of this application was (and continues to be) the capability of testing human (i.e., non-pilot) behavior in a multi-tasking context that parallels aviation tasks.

A number of improvisations and expedients were made in order to implement the biocybernetic system prototype incorporating the MAT Battery (see Fig. 1.). Pope and Bogart [24] introduced a conceptual model of HSA-inducing individual and situational factors and a methodology based on discriminant analysis of electrocortical frequency band powers to distinguish between hazardous and optimal states. However, this discriminant analysis methodology did not lend itself to the real-time tracking of operator state necessary for timely adaptive response. The psychophysiological literature [5,17,21,43] described shifts in EEG characteristics as attentional states fluctuated, which suggested that a ratio measure derived from the EEG might serve as a real-time responsive index of attentional state. This index was constructed to have higher values for subject states corresponding to greater degrees of mental engagement, that is, greater demands for operator involvement [25]. A sustained reversal in slope of the trend of such an index over a time window, essentially the time derivative of the index time series, was used as the criterion for indicating state change prompting an adaptive system response.

Recently, an independent research group [15] examined and expounded upon the capability of the biocybernetic system described by Pope et al. [26]. The concept of "performance equilibrium", which defines the high performance index, was underscored by Hettinger et al. as [15] the goal of an adaptive interface such that the human-machine system is maintained within the boundaries of a desired envelope with respect to some psychophysiological variable(s). Hettinger et al. describe a neuroadaptive interface as a system of computer-based displays and controls, which are driven by specified cognitive and/or emotional states of the user. This adaptation can alter the information presented to the user as well as modulate the control the user can exert on the system. This function may be thought of as psychophysiologically-based *modulation* of the system that the operator is consciously controlling by indirect means. This difference between modulation and control distinguishes the biocybernetic paradigm in the LaRC and ODU work from other brain-computer interface (BCI) work. This examination by Hettinger and colleagues identifies the strengths of this work and supports continued work on this line of research. Furthermore, while the previous research was thorough, it was not exhaustive and there are still many methodological and theoretical stones left unturned.

CURRENT RESEARCH AND FUTURE DIRECTIONS

Four applications of the closed-loop system design were proposed by Pope and Bogart [25] and Pope et al. [26]: 1) psychophysiologically adaptive automation; 2) validation of candidate psychophysiological indices of operator state; 3) evaluating an interactive system design by determining optimal human/system task allocation 'mixes,' and 4) a psychophysiological self-regulation training system based on the adaptive task concept. Of these, only the psychophysiologically adaptive automated system application has been researched to any extent, primarily by investigators at ODU [35]. Current and future research efforts will focus on the first and second application by examining various configurations of psychophysiologically adaptive automation as a means for maintaining effective operator state.

Current research efforts involve the use of a recently developed version of the Multi-Attribute Task Battery (MAT-B II), which contains the same tasks as the original MAT Battery with the addition of more extensive automation capabilities and greater experimenter control over the software application. An ongoing study uses an open-loop design in which experimental subjects operate the MAT-B II while the system steps through sixteen levels of automation from fully manual to fully automated. The EEG and ECG of experimental subjects are recorded during these interactions for post hoc decomposition into time and frequency domain variables and for statistical analysis. Subjects also complete self-reported measures of workload and input behavior is monitored throughout the task. In this initial open-loop phase the MAT-B II function is controlled by a script file and no adaptive automation occurs. Additional investigations are planned to examine the effects of mixtures of automation level on psychophysiological, self-report, and observational measures. The intent of these initial studies is to determine the effects of various levels of automation on operator state indices derived from EEG and ECG, including those from previous LaRC/ODU research and published research in the fields of psychophysiology, human factors, and human machine interface.

Developing a biocybernetic system requires answering the question: How are psychophysiological parameter changes to be interpreted meaningfully to drive adaptation? Empirical research and development are required to examine the couplings between neuroadaptive interface concepts and nervous system activity in real world situations. Investigations are necessary to provide practical information about how such systems should be designed to allow for further specification and efficiency of such systems. In order to continue the LaRC/ODU efforts it is necessary to apply a closed-loop paradigm, which involves psychophysiologically derived indices of operator state to drive the automation of the operational task. The follow-on work to the current open-loop investigations will involve an enhanced version of the MAT-B II capable of receiving inputs from a controller, which incorporates operator state indices into its automation mode decisions. This psychophysiologically adaptive automation capability will allow for validation of previous findings in the MAT-B II. Furthermore this capability will allow for validation of candidate psychophysiological indices of operator state

Selecting the psychophysiological signals for the task-modulating index is critical when implementing psychophysiologically-based adaptive automation. Pope et al. [26] demonstrated a method to evaluate the relative usefulness of candidate EEG indices for reflecting mental engagement in a task. In the initial biocybernetic system, candidate engagement indices were gleaned from the EEG literature on attention and vigilance. Recent clinical research, has employed a similar ratio construction as a diagnostic indicator in Attention Deficit Hyperactivity Disorder [19]. The problem of determining the relative usefulness of a cognitive index can be seen as one of determining the relative strengths of the functional relationships between the candidate indices and task characteristics (e.g., manual versus automatic modes) in a closed-loop configuration. This powerful method is an adaptation of a procedure first described by Mulholland [20] in a biofeedback context. The closed-loop index evaluation method offers one approach to validating competing candidate index definitions from the literature and from algorithmic methods [32,33], in the context of the closed-loop paradigm, the paradigm in which they will be employed in the planned PAS.

APPLICATION OF PAS-ENHANCED FLIGHT CONCEPTS: THE NATURALISTIC FLIGHT DECK

The Naturalistic Flight Deck (NFD) [38] is the implementation of a "clean-slate" design of a consistent and complete flight deck, which can serve as a platform for employing psychophysiologically adaptive automation to synergistically combine an innovative flight control design with self-regulation training. Modern automation design does not take pilot engagement into consideration; consequently, pilot state shifts between the extremes of boredom (when the automation is handling everything) and stress (when the automation returns control to the human or fails). The NFD is built on the concept of complementary automation or "complemation" (as contrasted with automation), which prescribes that the technology in the aircraft be applied with the goal of complementing the human (accentuating the pilot's strengths and compensating for his weaknesses) rather than usurping the pilot's role. One proposal for the NFD integrates state monitoring and mitigation to augment an innovative flight control design that is itself already designed to enhance pilot engagement - the H-mode. In automated environments, operator engagement may be maintained by a controller design such as the H-mode [10], a haptic control system that keeps the pilot engaged in anticipation of possible automation degradation. The H-mode based design, in which the pilot initiates significant flight behaviors (e.g., turns, takeoffs, altitude changes) at or near the time of execution (i.e., no lengthy preprogrammed route executions) while automation handles inner-loop control and fosters pilot engagement.

CONCLUSION

The applications of psychophysiologically-based adaptive automation systems in aviation hold great promise. As designed and experimentally implemented these systems have demonstrated the capability of improving operator performance in multi-task, human-machine systems. The potential for assessing operators in aviation, rail and highway transportation for the purposes of mitigating HSAs and increasing safety is very real. The future directions described point out some important areas yet to be fully examined empirically. The integration of a PAS into the updated Multi-Attribute Task Battery (MATB-II), will allow researchers in aviation and other areas interested in multi-tasking situations to explore the effects of neuroadaptive levels of workload and automation mixes on operator state. Inclusion of a PAS in the NFD represents one experimental operator/vehicle system concept currently in use to investigate these issues; defining the control parameters of such a cooperative vehicle still requires extensive research and development. Until these and other key factors are fully assessed the use of biocybernetic or neuroadaptive technology will remain limited to the laboratory. The promise of these types of systems underscores the need to continue investing in their development and evaluation as a viable technology for mitigating HSAs and improving safety.

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