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# Psychophysiology and adaptive automation

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**Abstract**

Adaptive automation is an approach to automation design where tasks are dynamically allocated between the human operator and computer systems. Psychophysiology has two complementary roles in research on adaptive automation: first, to provide information about the effects of different forms of automation thus promoting the development of effective adaptive logic; and second, psychophysiology may yield information about the operator that can be integrated with performance measurement and operator modelling to aid in the regulation of automation. This review discusses the basic tenets of adaptive automation and the role of psychophysiological measures in the study of adaptive automation. Empirical results from studies of flight simulation are presented. Psychophysiological measures may prove especially useful in the prevention of performance deterioration in underload conditions that may accompany automation. Individual differences and the potential for learned responses require research to understand their influence on adaptive algorithms. Adaptive automation represents a unique domain for the application of psychophysiology in the work environment.

*Keywords:* Psychophysiology; Automation; Aviation; Mental workload; Mental effort; Human performance; Adaptive systems

## 1. Introduction

One classic goal of human factors engineering is to ensure a good fit between the work environment and human capabilities (Wickens, 1992). The promise of psychophysiology as a tool to study mental workload in this endeavor is widespread, although not universally accepted (Kramer, 1991; Wilson & Eggemeier, 1991). Psychophysiological measures have the advantage when compared with other methods used to study mental workload (e.g., subjective

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ratings) because of their potential to yield real-time estimates of mental state. However, the rationale for having a real-time or continuous psychophysiological measure of mental workload in an applied environment is rarely expressed (cf., Hancock & Chignell, 1987; Kantowitz, 1987; Parasuraman, 1990). Is there an application for real-time assessment of mental state in the work environment beyond basic research on system development and operator training?

One workplace application for continuous assessment of mental state using psychophysiology exists, at least conceptually, and is known as adaptive automation (also adaptive aiding, adaptive function allocation). Adaptive automation includes the monitoring of operator state as one approach to regulate automation use (Rouse, 1988). The role of psychophysiology in adaptive automation draws from the biocybernetics program proposed in the 1970s (Gomer, 1980, 1981). The biocybernetics program had broad goals for the use of psychophysiology ranging from the development of new control channels to the adaptation of tasks in response to changes in workload. Adaptive automation, in contrast, has the singular objective to regulate automation for optimal system (human-machine) performance; and psychophysiological methodology is only one component in a multivariate scheme, which also includes critical event detection, operator preferences, and performance assessment.

In this paper we present the basic tenets of adaptive automation and discuss the role of psychophysiology in this application. Existing models from other areas of research are described and issues related to the use of psychophysiology in adaptive automation are reviewed. While preliminary ergonomic issues for the application of adaptive automation have been discussed (Parasuraman, Bahri, Deaton, Morrison & Barnes, 1992), the design of specific adaptive systems will need to consider the psychophysiological issues raised in this paper.

## 2. Automation and human performance

Humans can adapt to a variety of environments, and when able, will manipulate the environment to meet their needs. Because neither humans nor environments are infinitely adaptable, human capabilities and subjective preferences may be surpassed. The resulting mismatch between the environment and the individual can lead to performance deterioration or workplace stress (Gaillard & Wientjes, 1994; Hockey, 1986). One approach used to decrease the probability of a mismatch between the individual and the work environment is to increase the computer control or automation of tasks.

Automation changes the quality and quantity of mental work. The traditional form of automation is static automation. In this form, automation is all-or-none technology either performing a task for us or not. While there are many benefits of automation (e.g., relieving humans from the tedium of routine tasks), there is increasing evidence that static automation has costs. These costs include impaired decision making, manual skill degradation, loss of situational awareness, and monitoring inefficiency. With automation, the role of the operator shifts from active participant in a process to passive monitor. Compared with manual control conditions, monitoring workload increases to include not only the automated process, but also the state of the automated system and the automated system performance indicators (Wickens, 1992). The ability of the operator to achieve these monitoring goals, especially when the automation is not 100% reliable, may affect the safety of the entire system (Parasuraman, 1987).

Recent studies demonstrate that human operator detection of automation failures is degraded during static automation, where the assignment of tasks between the operator and automated system remains constant (Parasuraman, Molloy & Singh, 1993; Parasuraman, Mouloua & Molloy, 1994). Subjects were tested using a multi-task flight simulator with component tasks that could be automated. In the first study, non-pilots performed tracking and fuel-management tasks manually over several 30-min sessions. Simultaneously, an engine-status task under automation control had to be monitored. Subjects were required to detect infrequent and random automation 'failures' by identifying engine malfunctions not detected by the automation. In a separate condition, subjects performed only 'back-up' monitoring of the automated engine-status task, without the tracking and fuel-management tasks. For both experimental conditions, subjects were given extensive manual training on the engine-status task.

Subjects had high performance levels on the engine monitoring task when monitoring was the only task. Subjects were also nearly perfect in detecting automation failures when they did the engine-status task manually along with the tracking and fuel-management tasks. However, when the monitoring task was under automation control in the multi-task condition, the detection rate of automation failures degraded after only 20 min. The mean detection rate of automation failures dropped to 32%, even though subjects detected over 75% of malfunctions in the manual condition, and over 95% when monitoring was the only task. In a follow-up study, experienced pilots exhibited similar performance trends although their overall performance was higher than the non-pilot subjects (Fig. 1).

These results provide a clear indication of the cost of long-term static automation on system performance, and show that monitoring of automation is inefficient when subjects simultaneously perform other manual tasks. This phenomenon has been described as automation-induced complacency, and while difficult to define (but see Singh, Molloy & Parasuraman, 1993), complacency and decreased vigilance have been considered factors in several aviation safety incidents involving automated systems (Mosier, Skitka & Korte, 1994).

## 3. Adaptive automation (AA)

Given that both non-pilots and pilots are inefficient in monitoring automation failures for a task automated for long periods, how might monitoring be

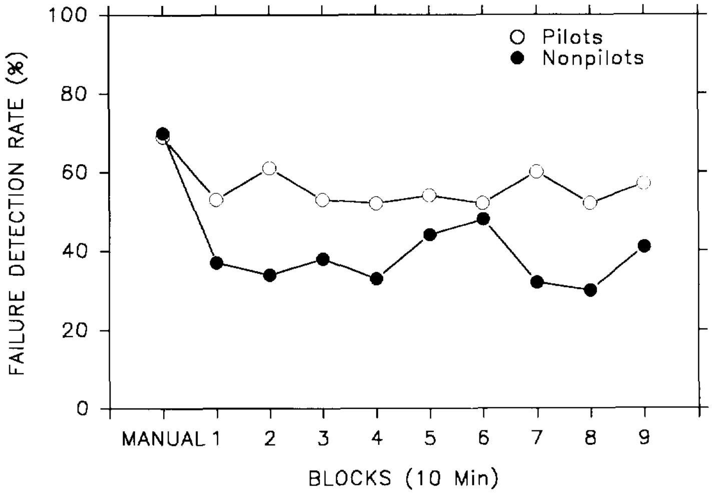


Fig. 1. Detection of automation failures by pilots (open circles) and non-pilots (filled circles) during manual control (MANUAL) and automation (blocks 1–9).

improved? Because monitoring without automation is generally efficient, one approach would be to insert brief periods of manual task performance into a long period of automation. This manual task 'reallocation' might have a beneficial impact on subsequent operator monitoring during automation and represents an example of adaptive automation. Adaptive automation has been proposed as a partial solution to the negative effects of static automation (Parasuraman et al., 1992; Rouse, 1988). Whereas static automation is viewed as an agent working for the operator, adaptive automation is viewed as an interactive aid working with the operator (Parasuraman et al., 1992; Scerbo, 1994).

In adaptive automation, the 'division of labor' or assignment of tasks between the human operator and automation is dynamically adjusted based on task demands, user capabilities, and total system requirements to promote optimal system performance. Adaptive automation, in contrast to static automation, allows for restructuring the task environment in terms of (a) what is automated, (b) how it is automated, (c) what tasks may be shared, and (d) when changes occur. In order to appropriately regulate automation, both the operator and the automated system must have knowledge of each other's current capabilities, performance, and state (Rouse, 1994; Scerbo, 1994). Operator states are sensed by a supervisory system, or predicted through a priori modelling of task demands. Next, in response to changes in workload, tasks are either taken away from the operator (i.e., automated) or offered back to the operator (i.e., return to manual). The quality of automation can range from complete task allocation to partitioning of a single task component between the human and computer (Rouse, 1988). Conceptually, a primary benefit of adaptive automation is that operator workload and fatigue can be regulated as a function of the shifting degrees of automation.

Three primary approaches have been proposed to generate criteria for adapting automation to the user (Parasuraman et al., 1992; Rouse, 1988): (a) critical events logic where automation is engaged consistently in response to an environmental stimulus; (b) model-based approaches where automation is 'scheduled' based on a priori models of optimal operator performance; and (c) continuous measurement of operator function and mental state. By providing a level of redundancy along with broader model specification, joint use of these three approaches in a 'hybrid' logic has been recommended as a way to produce stronger adaptive systems compared to those attainable using only one approach (Parasuraman et al., 1992).

The effect of a model-based approach to adaptive automation was tested in another study using the automated flight simulator described previously (Parasuraman et al., 1994). Pilots worked for three 30-min sessions, with two tasks under manual control (tracking and fuel management), and the third (engine-status monitoring) under automation control. The monitoring task was under automation control during the first session and part of the second session. At the midpoint of the second session, the monitoring task was reallocated to manual control. Following 10 min of manual performance, the monitoring task was again automated and subjects completed the rest of the second session and the entire third session with automation. A control group performed the task under automation control for all 3 sessions.

The detection rate of automation failures was not significantly different for the manual reallocation and automated control groups during the first 40 min spent with automation. As in the previous studies, monitoring performance under automation was poor. However, the detection rate for the manual reallocation group was significantly higher than for the automated control group after the 10-min period of manual performance (Fig. 2). The benefit, which averaged more than 50%, persisted through the end of the final 30-min session during which the engine-status task was automated.

Increased performance following rest or changes in task characteristics are often reported in studies on attention. However, the goal in adaptive automation is to strategically define the quality and duration of these changes. Guidelines to accomplish this have been developed to direct research in adaptive automation (e.g., Parasuraman et al., 1992).

Optimal adaptive logic design parameters such as automation level, duration, and cycle time, need to be identified along with key components useful for a hybrid approach. In addition, potential problems of adaptive automation have not been adequately identified, and some investigators worry that fully adaptive systems might be too unpredictable for human operators (Billings & Woods, 1994). Nevertheless, adaptive automation is recognized as an improvement over static automation because it emphasizes the capabilities of the human operator in contrast to the capabilities of technology (Mouloua & Parasuraman, 1994).

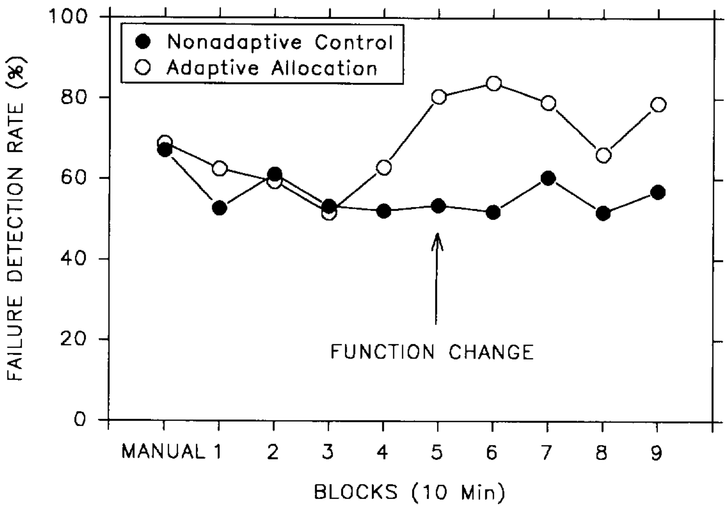


Fig. 2. Effects of manual task reallocation on detection of automation failures by pilots during manual control (MANUAL) and automation (blocks 1–9). In the Adaptive Allocation group (open circles) block 5 was a return to manual condition, followed by return to automation in blocks 6–9.

## 4. Theoretical frameworks

Physiological measurement in adaptive automation is predicated on the existence of an optimal state for the human operator in a given task environment (e.g., Gaillard, 1993; Hockey, Coles & Gaillard, 1986). Resource and capacity theories of information processing are central in this reasoning (e.g., Kahneman, 1973; Wickens, 1984) and they suggest that humans draw from a limited pool of resources when processing information. Kahneman (1973) stated that physiological measures of activation could be used to assess resource utilization or the expenditure of cognitive effort. Cognitive effort is viewed as an involuntary process produced by external task demands. Another type of effort, compensatory effort, is an energetic process under voluntary control and likened to motivation (Mulder, 1986). Both forms of effort are thought to be detectable through changes in physiological measures.

Hancock and colleagues (Hancock & Chignell, 1987; Hancock & Warm, 1989) and others (Gaillard, 1993; Hockey, 1986), expand on Kahneman's basic approach by considering the potential negative effects of underload on human performance, along with the often stated negative effects of overload. According to Hancock's model, both underload and overload produce psychological and physiological strain, detectable through psychophysiological measures. The strain arises because of a mismatch between the operator's current state and the desired state (e.g., Hancock & Warm, 1989; Hockey, 1986).

Hockey's model of human state regulation (Hockey, 1986) provides an outline for psychophysiology in adaptive automation. In this model, a state-monitor within the operator compares the current cognitive state with the target state required to accomplish their goals. Following this comparison, four pathways of action are available: (a) change cognitive state to match the target; (b) change the target state to match the current cognitive state; (c) change factors in the environment impeding cognitive state; and (d) do nothing at all. In adaptive automation the measurement of physiological state augments the operator's state-monitor to maintain functionality when it becomes biased or insensitive to a mismatch between states. Hockey's model suggests appropriate points for intervention by an adaptive system.

For example, assuming a hybrid adaptive system using critical events detection, workload or performance modelling, performance assessment, and psychophysiological measures, two scenarios can illustrate intervention points based on Hockey (1986). First, if the human operator accurately assesses target state, current state, and the mismatch between states, and then initiates a change in current state, an adaptive system could use psychophysiology to monitor this process. If the operator was not able to reduce the mismatch the system could offer to the operator a change in the levels of automation. The offer to increase levels of automation would serve two functions to reduce the mismatch: (a) revision of the target state; and (b) modification of the environment. Second, if the human operator fails to detect a mismatch between states the adaptive system could revise the task environment via warnings or shifting levels of automation to re-engage the operator. The adaptive system would detect the mismatch using a previously generated database of 'optimal' physiological states for the operator. Using control paths outlined in Hockey (1986), changing the environment could serve two roles: (a) revision of the target state to reduce the mismatch; or (b) increasing the mismatch in an attempt to provoke the subject to allocate the requisite effort. This would also be appropriate if the operator was aware of a mismatch but failed to take action to resolve it, as in underload or fatigue.

It should be noted that the emphasis in adaptive automation has been on the prevention of overload and it has even been suggested that tasks should only be removed from a human operator (i.e., automated), never given back to them (e.g., Rouse, 1988, 1994). However, it is clear that adaptive automation may be a beneficial approach to alleviate an underload condition by returning an automated task to the operator. Although acceptance of the potential for underload to have negative consequences is not universal (e.g., Redondo & Del Valle-Inclan, 1992) psychophysiological investigations of underload in complex task environments and applied domains are becoming more prevalent (e.g., Braby, Harris & Muir, 1993; Roscoe, 1993).

## 5. The dual role of psychophysiology in adaptive automation

Psychophysiological measures are an important part of adaptive automation in two ways. First, they can provide information on the mechanisms underlying performance changes corresponding to changes in automation, and help guide the development of model-based and hybrid approaches. This investigatory role of psychophysiology can be characterized as the developmental approach. Second, they may provide unique information about the human operator that could be input to a hybrid adaptive logic, and thus assist in the dynamic structuring of the task environment. This role of psychophysiology can be characterized as a regulatory approach. These two approaches are not isolated from one another, but exist as complementary applications of psychophysiology to adaptive automation.

Each approach exists on opposite ends of a 'continuum of feedback'. This continuum describes the hypothetical time course required for information and principles generated using psychophysiological methods to effect change in the work environment. The developmental approach is placed at the long latency endpoint because it can lead to changes in the work environment on a scale from a few days to several years. In this form, the use of psychophysiological methods in the study of adaptive automation is similar to contemporary applications of psychophysiology in the study of mental workload and attention (e.g., Kramer, 1991). The regulatory approach is placed at the short-latency endpoint because psychophysiological data may influence the work environment, when input to adaptive logic, on a scale ranging from minutes to seconds. This is the ultimate application of psychophysiology in adaptive automation, similar to the goals of biocybernetics (e.g., Gomer, 1980, 1981).

Because the goal for psychophysiology in the developmental role is to understand the effects of variations in automation on human performance, and thus facilitate the design of adaptive systems, the measures used do not necessarily have to be able to migrate to the regulatory role. The success and effects of interventions, such as changes in task allocation, can be assessed using psychophysiological measures and other tools (e.g., Kantowitz, 1992). Beyond providing an index of mental workload and effort, psychophysiological measures in the developmental role could be especially useful in the assessment of other human responses relevant to the optimal design of an automated system. For example, evaluating operator response to shifts in the levels of perceived and actual control (Dember, Galinsky & Warm, 1992; Gaillard, 1993; Hockey, Briner, Tattersall & Wiethoff, 1989) and other factors associated with stress in the workplace (e.g., Gaillard & Wientjes, 1994).

In the regulatory role, the end goal is to use psychophysiological measures to aid in the operation of an adaptive automation environment. Whether psychophysiological measures will be valuable in this application is dependent on the identification of valid and reliable indices and the ultimate design of a hybrid system. We propose a hierarchical structure as a way to organize the various logic components in a hybrid model. In this structure, an individual component in the adaptive logic is assigned a weight for its contribution to the overall decision process. Components associated with models of automation usage, performance modelling, and critical events are proposed to have greater weight than measures of operator function or state, in part because they can be more clearly specified a priori. Physiological measures are positioned in a support role underneath these factors in most situations. They would receive greater weight in some circumstances because they may be one of the primary ways to detect when an operator has the potential to regain manual control of a task or is incapacitated. The reason for this secondary placement in the hybrid hierarchy is that the technology for modelling and intervention using other components is further advanced than what exists for psychophysiological measures of operator state. However, allowances should be provided for in any adaptive logic to insert psychophysiological measures as they are identified and become more reliable indices of mental state.

Progression along the continuum from the developmental approach to the regulatory approach is not a requirement for the success of psychophysiology in adaptive automation. Progress is realized through either alone. Effective application of psychophysiology in the regulatory role may require years of effort and considerable maturation in technology. The criteria required for psychophysiological measures to enter the regulatory phase are much stricter than in the developmental phase because they become part of a closed-loop system operating in real time. The dual role framework, however, offers a natural delineation of the two roles of psychophysiology so that research on adaptive automation can progress with clearly defined objectives concerning the utility of psychophysiological methods.

## 6. Selection of candidate psychophysiological measures

Identification of candidate psychophysiological measures for use in adaptive automation can be facilitated if the dual role framework is considered. For example, much of the research in adaptive automation is centered on the use of psychophysiological measures to aid in the development of optimal approaches to using automation. Because the developmental role of psychophysiology in adaptive automation is similar to other applications in psychophysiological research, the often stated criteria of specificity, diagnosticity, and intrusiveness for selecting workload assessment techniques also hold in principle for research on adaptive automation (Kramer, 1991; O'Donnell & Eggemeier, 1986; Wilson & Eggemeier, 1991). Yet, strict interpretations of sensitivity, specificity, and diagnosticity should not constrain research in this area. For example, many psychophysiological measures are sensitive only to imposition or removal of a task and not small gradations in workload. This type of 'coarse' state assessment is not necessarily a problem for research on adaptive automation because workload assessments on a binary scale may provide significant information to adaptive logic (e.g., on-task versus off-task).

Another concern often accompanying psychophysiological measures of mental workload is their potential for contamination by emotional states. This concern, while relevant at a theoretical level, might be largely irrelevant to applied efforts. There is evidence that psychophysiological measures traditionally considered immune to emotional processes (e.g., ERP) may be affected under some conditions (e.g., Rosenfeld, Johnson & Koo, 1993). Emotional and energetic states (e.g., complacency, motivation, frustration) may be related to performance in automated environments, and under high stress conditions they may be key determinants of performance (e.g., Gaillard, 1993; Hockey et al., 1986; Svensson, Angelborg-Thanderz & Sjoberg, 1993). It seems that exclusion of any psychophysiological measure for use in adaptive automation on this basis is premature.

When choosing measures for the regulatory role of psychophysiology in adaptive automation, more stringent selection criteria will be required. Ultimately, beyond the basic criteria used to assess efficacy of psychophysiological measures of mental workload, more rigorous diagnostic criteria traditionally associated with test sensitivity and specificity will be required. In addition, because the cost of psychophysiological measures is relatively high, in terms of intrusiveness and technical requirements, their use will be dependent on their explanatory power. If the gain in predictive value does not offset the cost of implementation, they may only exist to aid the regulation of automation in laboratory tasks and never enter the applied realm.

Our experiences with heart rate variability (HRV) illustrate some issues involved with the selection of a candidate measure for adaptive automation research. HRV is one psychophysiological measure often showing greater efficacy in the detection of gross changes in workload in contrast to refined gradations (Jorna, 1992). Although HRV is generally recognized to reflect variations in cognitive effort, it may actually reflect a mixture of cognitive processing demands and energetic processes (i.e., compensatory effort) depending on the particular task environment. For example, a recent study (Byrne, 1993) examined the psychophysiological responses of 42 subjects, aged 18–30 years. while they worked on a task simulating a semi-automated air traffic control (ATC) task environment. The task lasted for 42 min and required subjects to detect critical events on the simulated radar screen (e.g., loss of transponder for an aircraft target, two aircraft at the same altitude). The overall group response was a linear increase in HRV with time-on-task. However, individual differences in the way subjects approached the task produced distinctly different profiles of HRV response. Subjects reporting high levels of effort showed significant suppression of HRV from baseline to task performance while subjects reporting low levels of effort showed a linear increase in HRV. Subjects showing initial suppression in HRV also showed faster reaction times to the critical events. Thus, in this task environment, which places subjects in the role of a passive monitor, HRV appears to have indexed the engagement of voluntary or compensatory effort. In subsequent studies, involving a multi-task environment requiring subjects to monitor for infrequent events while performing a compensatory tracking task, we have found only group decreases in HRV in response to task load and no relationship to individual differences in subjective ratings of effort (e.g., Byrne, Chun, Hilburn, Molloy & Parasuraman, 1994).

Two points can be drawn from this example relevant to future research on adaptive automation. First, psychophysiological measures which cannot discriminate between levels of task load, but can discriminate between task and rest conditions may have utility in the detection of underload. For example, increases in HRV in response to task loading in the ATC task could be classified as an inappropriate response that results in task modification or alerting to re-engage the subject. However, this leads to a second point: the interpretation of psychophysiological measures of workload may be difficult when applied to issues of underload. That is, the contribution of energetic aspects such as motivation and effort may be confounded with task aspects. In an underload condition, the task characteristics (short-term memory demands, time pressure) which elicit cognitive effort may not predominate and psychophysiological profiles may be more dependent on variations in compensatory effort. Moreover, other energetic factors associated with stress and coping may come into play during underload conditions in contrast to overload conditions. With HRV, under what task conditions do changes reflect (a) how hard subjects want to work (i.e., compensatory effort) or (b) how hard subjects have to work (i.e., cognitive effort)? These questions must be reconciled because the resulting adaptive strategies are distinct: if the decreases in HRV in the ATC task are interpreted as overload, a change in the environment to alleviate this condition are in order; however, if they reflect appropriate effort invested in the task, such a change may actually be counter-productive. It has been recognized that some psychophysiological measures may index task difficulty while others index compensatory effort, and still others index both task difficulty and compensatory effort (Mulder, 1986). Based on our findings, HRV while conventionally recognized as an index of cognitive effort or task difficulty, may actually be an example of a psychophysiological measure that may index both cognitive effort and compensatory effort, depending on the particular application. This type of ambiguity in interpretation is where hybrid approaches to adaptive automation considering critical task events, performance measures and other possible metrics may prove useful.

## 7. Existing 'adaptive' applications

Existing psychophysiological research does not provide adequate information on how potential metrics might be used to regulate mental state in a closed-loop environment. However, guidance may be found in other research domains.

For example, countermeasures used against + Gz induced loss of consciousness in military aviation provide an analog of an adaptive aiding system based on critical events logic (i.e., the onset of high + Gz). There are also proposed countermeasure systems using physiological measures (EEG, ECG) to index operator state, besides + Gz force, to detect unconscious states (Moore, Foley, Reddy, Kepics & Jaron, 1987; Whinnery, Glaister & Burton, 1987). These multivariate systems represent analogues to hybrid adaptive schemes.

In the domain of medical research, there exist several models for the direct closed-loop control of physiological state under anesthesia, for example in the regulation of blood pressure (e.g., Martin, Schneider, Quinn & Smith, 1992). Because physiological measures are indirect estimates of mental state, more relevant to adaptive automation are medical models using indirect estimates to control system function. Few models of this type exist, however prototypes using indirect estimates such as EEG in the closed-loop regulation of anesthetic state have been described (e.g., Schwilden, Stoeckel & Schuttler, 1989). Still, it has been suggested that due in part to the difficulties involved in identification of what defines an indirect estimate of anesthetic state, the automated maintenance of anesthesia will be difficult if not impossible (Gaba, 1994). It would be prudent to monitor whether these issues are resolved in the future because of the similar difficulty that exists for defining an estimate of mental state.

Even closer to the goals of adaptive automation is a system described by Yamamoto and Isshiki (1992) using psychophysiological measures in a closed-loop system to maintain an alert state. A simple control system was designed using continuous assessment of arousal as input and an auditory alarm as output. Spontaneous variability in palmar skin conductance was used to estimate arousal, and the alarm sounded when 3 min elapsed without a spontaneous response. According to the authors this system regulated mental state and reduced the potential for sleep onset. This system apparently functions as a state-monitor to identify a mismatch between the current and desired state. After receiving an indication that the mismatch exists through the auditory alarm, the subject expends effort to resolve the discrepancy.

Similar 'alertness indicators' have been proposed in the past (see reviews in Parasuraman, 1983, 1990; Satchell, 1993). These include simple threshold-level indicators based on EEG, EOG, and head movements, and more complex systems based on multivariate analysis of several physiological signals. These systems have been proposed for use in long distance driving and process control, but systematic evaluation of their efficacy in real settings is lacking.

A prototype adaptive automation strategy using psychophysiological measures was recently described (Pope, Bogart & Bartolome, 1995). This system used parameters derived from continuous EEG and was designed to provide an index of subject 'engagement' in a multi-task environment consisting of tracking, system monitoring and resource management. When EEG parameters suggested loss of engagement, subjects performed the tracking task manually; when engagement on the task was identified the tracking task was automated. Building on basic control theory, an iterative procedure was established comparing 'normal' system response using a negative feedback model to system response using a positive feedback model for various EEG parameters. For example, system state was evaluated in a negative feedback mode (EEG index of loss of engagement leads to manual control) and this behavior was contrasted with behavior in a positive feedback mode (EEG index of loss of engagement results in automated control). This strategy forms an essential approach to evaluating potential measures or parameters in adaptive automation logic. Specifically, the problem of how to identify psychophysiological measures which provide for stable response under negative feedback and unstable response under positive feedback control conditions. This study shows that EEG parameters for negative feedback control can be identified. Additional studies will be required, however, to find whether this physiologically-based method of adaptive control also regulates operator performance, operator subjective effort, and total system performance, none of which were systematically examined in this study.

Efforts to regulate adaptive automation using psychophysiological measures might build on similar efforts in other domains. Existing models can provide guidance on controlling artifacts in feedback logic, obtaining initial reference values, and the difficulties involved in using indirect measures of state in a closed-loop system. Finally, the potential complexity of adaptive algorithms using psychophysiological measures can be appreciated. For example, the simple 'alertness indicator' described above (Yamamoto & Isshiki, 1992) used only skin conductance, detected only two states, and contained a single decision making rule. In contrast, multivariate psychophysiological models discriminating several states have been proposed with over 100 decision making rules (e.g., Varri, Hirvonen, Hasan, Loula & Hakkinen, 1992).

## 8. Psychophysiology in adaptive automation: problems and considerations

The potential confounds and technological obstacles associated with the study of psychophysiological estimates of mental workload apply also to adaptive automation. These include, for example, obtaining artifact free data, knowledge about measurement characteristics of the signals (reliability, stability), equipment and other technology requirements (Kramer, 1991). The use of psychophysiology in adaptive automation merits additional consideration because of real time, interactive requirements. The areas of concern listed below are not exhaustive, but represent fundamental sources of variance affecting the placement of psychophysiology in the hybrid adaptive automation hierarchy.

### *8.1. Speaking*

The effects of speaking on psychophysiological measures of mental workload are in many respects unknown because they are comparatively under-evaluated in existing research. There is some evidence that speaking can affect psychophysiological measures (e.g., Sirevaag, Kramer, Wickens, Reisweber, Strayer & Grenell, 1993; Sloan, Korten & Myers, 1991). Speaking in applied settings can range from command response, characterized as infrequent short bursts of speech, to monologue conditions. Without some consideration of the effects of speaking on psychophysiological measures, an adaptive system may become unstable with variations in speaking. Research is required to document the effects of variations in speaking on psychophysiological measures; and these effects must be included in adaptive system design.

### *8.2. Individual differences*

Because the ultimate efficacy of adaptive systems using psychophysiology is based on single subject analysis, individual differences will be difficulties to overcome. Individual differences in psychophysiological response in applied environments are prevalent (e.g., Rose & Fogg, 1993), and it has been recommended that each individual serve as their own control (e.g., Roscoe, 1993). Circadian variation in psychophysiological measures may also affect their utility in adaptive automation (e.g., Aasman, Wijers, Mulder & Mulder, 1988). Gross models may be derived from the analysis of group data, however individual differences dictate that hypothesis testing should be conducted at the level of single subjects. Calibration strategies may need frequent application (see below) to establish initial parameters for feedback models which will improve the accuracy of the adaptive algorithm. The chronic application of an adaptive algorithm in the work environment may mean that replicable conditions become the exception rather than the rule because of time-of-day effects, variations in life stresses, and medication, to name a few. These variations may limit the usefulness of notions such as reliability and stability when selecting measures.

### *8.3. Problem of environment*

Many proposed applications of adaptive automation are in transportation (e.g., long distance driving, aviation); domains with diverse environmental qualities. Using psychophysiology in these environments will require continuing advances in the area of basic methodology to provide good quality signals. In-flight acquisition of multivariate psychophysiological measures have increased, although not without subject attrition because of data quality (e.g., Wilson, Fullenkamp & Davis, 1994 – 3 of 10 subjects). Because of the ability for physical workload to disrupt autonomic psychophysiological measures, variations in physical workload both across and within proposed application environments may differentially affect adaptive strategies. For example, the effects of physical workload on estimates of mental state are considered small in commercial aviation (Roscoe, 1993) while in some aspects of military aviation physical workload is considered significant (Wilson, 1993). Finally, the potential for motion sickness is associated with transportation. Both motion sickness and pharmacological countermeasures can disrupt autonomic activity (Golding, 1992; Uijtdehaage, Stern & Koch, 1993), possibly interfering with adaptive algorithms using psychophysiology.

### *8.4. Learned responses*

One unique problem for psychophysiology in adaptive automation is the potential for learned responses to compromise the adaptive logic. Research on biofeedback has demonstrated the potential for many psychophysiological measures to become conditioned (e.g., Ax, 1990; Hatch, Borcherding & German, 1992; Roger & Galand, 1981). It is conceivable that operators may detect the algorithms that contribute to variations in task allocation through repeated exposure to a particular adaptive system and voluntarily manipulate their physiology to change the task. Learning to control physiological response in this way has the potential to facilitate adaptive logic and total system performance if the goals of the adaptive logic are consistent with those of the operator. Because this may not always be true, any adaptive logic using psychophysiology should ensure that learned responses do not subjugate the goals of the adaptive system. One strategy to reduce the opportunity for the operator to learn what physiological response patterns invoke changes in automation would be to provide for reallocation of function or tasks outside the scope of the adaptive logic (e.g., randomly, but still within the assessed capabilities of the operator).

### *8.5. Operator expertise*

As operators become more familiar with an automated system, through training or time on task, the strategies they use to interact with the system may change. The selection of different strategies to accomplish the same goal is problematic for the estimation of operator workload (Goettl, 1991). This must be considered because variations in cognitive strategy, such as automatic versus controlled processing (e.g., Schneider, Dumais & Shiffrin, 1984), may also produce different physiological responses (Mulder & Mulder, 1987). As described above, this is an individual difference factor that may be controlled by frequent calibration of an adaptive system. It is possible that certain operator strategies may negate the utility of physiological measures in an adaptive logic.

## 9. Research approach

Research examining the utility of psychophysiology in adaptive automation has been rare. Nevertheless, physiological measures are likely to be considered in the design of adaptive systems, either in isolation or in combination with other measures. It is therefore helpful to outline factors to be considered in the development of these systems. A fundamental consideration is that research must be closely linked to the applied environments where this technology will be deployed. This requirement affects research design on three levels: (a) task selection; (b) subject selection; and (c) interfaces with other adaptive automation concepts.

Concerning task selection, whereas complex tasks will be required in later stages of research, basic research using unidimensional and refined tasks is essential for the development of a set of psychophysiological 'adaptive automation design principles'. This could be accomplished through iterative open- and closed-loop testing of candidate measures. These principles would include classification of measures, parameters, levels of redundancy, and levels of sensitivity for various tasks. By drawing heavily on a substantial base of basic existing psychophysiological research on mental workload, information processing, and attention, critical task characteristics and optimal psychophysiological measures could be identified for this effort.

Concerning subject selection, because the end user of any adaptive system will likely be an expert, it would be advantageous to use highly trained subjects for research in this area. The feedback models generated using novices may be quite different from those generated using experts. Through repeated testing of individual subjects, guidelines on the magnitude of day-to-day variations in model effectiveness could be developed.

Finally, determination of the utility of psychophysiological measures as inputs to adaptive automation cannot be made in a vacuum, but instead must be tied ultimately to other measures of operator functioning and performance modelling. Psychophysiological measures should be approached as complementary tools to augment and refine adaptive automation and not isolated regulatory factors. At the level of the adaptive logic, integration of psychophysiological measures with other system parameters and determining priority requires application-specific design considerations. For example, psychophysiological measures of incapacitation may be considered singularly and lead to automated takeover without operator consent in a high performance military aircraft. In contrast, psychophysiological measures of sleepiness may be considered along with tracking performance and lead only to an advisory warning not to use cruise control in a highway bound automobile. Both examples are variations on the adaptive automation concept. Psychophysiological measures have the potential to yield data on information processing on a per event basis. However, without some type of hierarchical constraints placed on these data, the potential exists for task regulation to occur at a pace perceived by the operator as over-intervention by an inanimate peer. Issues of operator consent as tasks are added and shed in adaptive systems will be an important design issue. Under many circumstances, psychophysiology may signal out-of-bound conditions that the adaptive logic would then further analyze using other operator state channels (e.g., performance, self-report, etc.) before offering a corrective action to the operator. Ultimately the utility of psychophysiological measures in a hybrid adaptive automation scheme requires that they contribute sufficient predictive capability to the model to offset their cost to obtain.

## 10. Summary and conclusions

Psychophysiology is an integral component in adaptive automation as a non-invasive method to assess operator state. Beyond their potential role as an input signal to adaptive logic in the regulation of automation, psychophysiological measures can provide information on the mechanisms underlying performance changes during the development of adaptive systems using model-based logic. Psychophysiological measures have been emphasized in this review, however they represent only some of the strategies available in adaptive automation. It has been suggested that research on adaptive automation will be most successful through adoption of a hybrid approach that considers multiple aspects of operator state (Parasuraman et al., 1992).

Researchers studying automation have suggested that the adaptive automation concept may offer one of the better ways of implementing automation known to date (Mouloua & Parasuraman, 1994); as research in this area continues, it offers a directed application for the study of psychophysiology in the work environment.

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