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THEORY AND DESIGN OF ADAPTIVE AUTOMATION IN AVIATION SYSTEMS

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Recent technological advances have made viable the implementation of intelligent automation in advanced tactical aircraft. The use of this technology has given rise to new human factors issues and concerns. Errors in highly automated aircraft have been linked to the adverse effects of automation on the pilot's system awareness, monitoring workload, and ability to revert to manual control. However adaptive automation, or automation that is implemented dynamically in response to changing task demands on the pilot, has been proposed to be superior to systems with fixed, or "static" automation. This report examines several issues concerning the theory and design of adaptive automation in aviation systems, particularly as applied to advanced tactical aircraft.
An analysis of the relative costs and benefits of "conventional" (static) aviation automation provides the starting point for the development of a theory of adaptive automation. This analysis includes a review of the empirical studies investigating effects of automation on pilot performance. The main concepts of adaptive automation are then introduced, and four major methods for implementing adaptive automation in the advanced cockpit are described and discussed.

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Executive Summary

Recent technological advances have made viable the implementation of intelligent automation in advanced tactical aircraft. The use of this technology has given rise to new human factors issues and concerns. Errors in highly automated aircraft have been linked to the adverse effects of automation on the pilot's system awareness, monitoring workload, and ability to revert to manual control. However, *adaptive automation,* or automation that is implemented dynamically in response to changing task demands on the pilot, has been proposed to be superior to systems with fixed, or "static" automation. This report examines several issues concerning the theory and design of adaptive automation in aviation systems, particularly as applied to advanced tactical aircraft.

An analysis of the relative costs and benefits of "conventional" (static) aviation automation provides the starting point for the development of a theory of adaptive automation. This analysis includes a review of the empirical studies investigating effects of automation on pilot performance. The main concepts of adaptive automation are then introduced, and four major methods for implementing adaptive automation in the advanced cockpit are described: (1) critical-event logic; (2) pilot workload measurement; (3) pilot psychophysiological assessment; and (4) pilot performance modelling. Important theoretical, technical, and practical issues concerning each of these methods are discussed.

To be effective, adaptive systems should be designed in accordance with a *human-centered* philosophy of automation. Some preliminary guiding principles for implementing adaptive automation in the cockpit are discussed. Design guidelines must currently be based on conceptual analyses because of the lack of empirical evidence concerning the impact of automation (adaptive and otherwise) on the human operators in aviation systems. Research strategies by which further evidence may be gained are discussed.

Introduction and Overview

Mission functions in modern tactical aircraft, and the nature of the threat pilots of such aircraft face, have grown more complex over the years. As a result, there has been a commensurate need for automation of cockpit functions to cope with this increased complexity. Several recommendations have been made in recent years to automate aircraft systems in the belief that automation technology will improve performance and expand tactical capabilities (National Research Council, 1982; *Defense News*, 1989). Recent technological advances have made the incorporation of intelligent automation a viable alternative in tactical aircraft. The Advanced Technology Fighter (ATF) and its Navy version, the NATF, are examples of aircraft where automation technology is being evaluated for incorporation in the cockpit. Other Navy efforts which propose to use advanced automation technology include the Advanced Technology Crewstation and KOALAS programs at the Naval Air Development Center. The latter is an intelligent, man-in-the-loop, architecture that is presently being demonstrated as a means to integrate real-time expert systems into a decision-support system for E-2/F-14 applications.

The introduction of automation technology in aircraft, as well as in other systems such as process control, has given rise to some new human factors issues and concerns. For example, the ability of the pilot to intervene effectively when an automated subsystem fails is one of the key issues in automated cockpits (Wiener, 1988). Other difficulties that operators of automated systems may face include loss of system awareness and manual skills degradation (Norman, Billings, Nadel, Palmer, Wiener, & Woods, 1988). These kinds of problems may be characteristic of complex systems in which automation is implemented in a fixed or "static" manner. In contrast, systems in which automated aids are implemented dynamically, in response to changing task demands on the operator, may be less vulnerable to such problems. It has been proposed that systems with *adaptive* automation[1] are superior to conventional automation because they provide for regulation of operator workload and vigilance, maintenance of skill levels, and task involvement (Hancock et al., 1985; NADC, 1989; Noah & Halpin, 1986; Parasuraman & Bowers, 1987; Rouse, 1976, 1988; Wickens & Kramer, 1985). More generally, systems in which tasks and functions are allocated flexibly to human operators and automated subsystems may provide for more effective user-system interaction.

This report examines several issues concerning the theory and design of adaptive automation in aviation systems.[2] The emphasis throughout is on the cognitive, pilot-automation interaction issues that

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[1] Also referred to as "adaptive aiding" and "adaptive function allocation."

[2] The behavioral literature on automation issues in aviation is more highly developed for commercial than for military aviation. We recognize that there are important differences between the two spheres of aviation, and

play a role in adaptive systems[3]. After a brief introduction to the concepts and history of aircraft automation, we consider some of the benefits and problems associated with "conventional" aviation automation. The few laboratory studies on the effects of automation on human performance are then reviewed. Next, adaptive automation concepts are introduced, and the four main methods for implementing adaptive automation in the advanced cockpit described. Training issues for effective use of adaptive systems are discussed next, followed by a discussion of preliminary design issues and guiding principles for implementing adaptive automation in the cockpit. Design guidelines must currently be based for the most part on "armchair" analysis and on opinions based on previous experience with automated systems. There is a paucity of *empirical* evidence in these areas, particularly concerning the efficacy of adaptive automation. As we identify some of these conclusions, we emphasize their tentative nature and suggest research strategies by which further evidence may be gained. For example, there is little empirical work showing whether pilots can use adaptive aids efficiently in the cockpit[4] and whether aircraft with adaptive aids (such as in Lockheed's Pilot's Associate program) will in fact be immune from some of the problems that have arisen with more conventional automation.

What Is Automation?

The word "automation" has so been widely used as to have taken on a variety of meanings. Nevertheless, several authors have discussed the concept of automation and tried to define its essence (Edwards, 1977; Norman and Orlady, 1989; Wiener, 1985). The American Heritage Dictionary (1976) provides a simple definition: "automatic operation or control of a process, equipment, or a system." This definition is general but straightforward. Wiener and Curry (1980) provided a more colorful definition of automation as "a collection of tyrannical self-serving machines. " This definition emphasizes that people perceive automation from different perspectives. Those who view automation from a mechanical point of view consider it to be an ensemble of "autonomous machine systems;" whereas those who are concerned

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that automation issues relevant to one area may not be significant for the other. For example, the problem of low levels of workload and boredom that have been reported for automated commercial airliners (Wiener, 1987) may be less of a problem in military aircraft (except, for example, long-haul transport aircraft such as the C-5 and C-141).

[3] Interface design is an important aspect of adaptive system design that will not covered in detail in this report. Analyses of aviation accidents in automated aircraft have shown that a number of errors have resulted from poor interface design (Norman et al., 1988). The representation of tasks and functions that are carried out by automation is a critical element of adaptive system design.

[4] See, however, Geddes (1986), for a feasibility study of the use of adaptive automation in the F/A-18 fighter aircraft.

with information management view automation as a new information system with enhanced capabilities (such as those found in diagnostic systems) (Woods, 1988).

Definitions of automation as applied to aviation systems are similarly diverse. At one extreme, there is a tendency to consider any technology addition to the cockpit as automation. At the other extreme, only devices incorporating expert systems have been considered to be automation. A simple rule of thumb to guide a middle ground between these two extremes would be to define automation as : *a device that accomplishes (partially or fully) a function that was previously carried out (partially or fully) by the pilot.* It is also useful to think of automation as a continuum rather than as all-or-none. The concept of "levels of automation" has been discussed by a number of authors (McDaniel, 1988; National Research Council, 1982). At one extreme of "total manual control" the function is continuously controlled by the pilot. At the other extreme of "total automation" all aspects of the function (including its monitoring) are delegated to a machine so that its operation is not visible to the pilot. In between these two extremes lie different degrees of participation in the function by pilot and automation. McDaniel (1988) identified 10 such levels. For example, in his level 9, *monitored automation*, the automation carries out a series of operations autonomously, while the pilot is able to monitor the operations but cannot change them. However, in McDaniel's level 6, *consent automation*, the automation displays a pending action to the pilot and requires the pilot's consent before it can carry out the function. Lower levels of automation would require the user to designate functions and/or define functions.

Adaptive automation has been proposed as a means for further increasing the number and flexibility of levels of automation in the cockpit. One outcome of this concept is that the adaptive system could select its own level of automation, depending upon the operating environment and pilot performance. The feasibility of this approach and its impact on operator and system performance is poorly understood. At present, the only consensus in the design of adaptive automation systems seems to be that the philosophy of the operator's role in the system will be critical. Typically, it is argued that the operator must interact with the automation as an executive, and as such provides consent to the level of automation assumed by the system (e.g. McDaniel's (1988) level 6 automation above). This has been deemed crucial in the Pilot's Associate program because of issues related to maintenance of pilot situational awareness and pilot acceptance. (System actions taken without pilot consent are envisaged only when failure to take action will have immediate, dire consequences.) Of course, this itself has additional implications for system performance because of the resultant impact on pilot workload. These implications are also discussed further below.

Automation thus encompasses a wide range of technology, from simple control devices to complex, subsystems involving machine intelligence. As these technologies have been introduced, perceptions and definitions of the the role of automation have changed continuously. For example, one trend that Rouse and Morris (1986) pointed out was a change in automation's role from an assisting device for people to

a replacing one. The rate of technological progress has varied from domain to domain, so that perceptions of automation have varied accordingly. In aviation, automation advances have been particularly rapid.

Automation in Aviation: Historical Background

Early aircraft automation was primarily concerned with the control of the aerodynamic surfaces of the aircraft. Control was achieved through the use of gyroscopic devices which served to stabilize the aircraft attitude by activating wing-warping and controlling roll and pitch. Gyroscopic stabilizers have been widely used to control aircraft since their first test on steam-powered flying machines (Pallett, 1983). At the beginning of World War II gyroscopic devices were incorporated into the "autopilots" in many long-range aircraft. Later, the navigational functions in aircraft were facilitated by the introduction of very high frequency omnirange (VOR). By the late 50's sensors provided the pilot precise data regarding magnetic heading, altitude, and position. In the 60's electronic devices were introduced which provided for such automatic flight capabilities as automatic landing, control of power and flight path, and so on, first seeing service in such aircraft as the DC-10, L-1011 and other commercial aircraft.

By the end of the 1970's a further step was taken toward sophisticated automation by integrating the area navigation system in the autopilot. It was at about this period of time that the first safety concerns about automation in the cockpit became the topic of the hour (US House of Representatives, 1977). Conclusions were drawn from aviation accidents and incidents that proper human factors principles should be considered while introducing automation (Wiener, 1977; Wiener & Curry, 1980). Automation technology continued to be developed and introduced largely independently of these concerns. One major development was the implementation of more flexible electronic CRT displays. This was followed by the addition of automated system management devices. These new automated systems enabled vertical as well as horizontal automated navigation and guidance, and also provided pilots with better flight path precision and maximum fuel economy. The new Airbus 300 series of aircraft, along with the Boeing 757-767 and the McDonnell Douglas MD-11 represent the most highly automated commercial aircraft yet, and represents the culmination of a long period of automation technology development.

Automation of flight control functions has progressed to the point that control can be achieved when manual control is no longer possible. In all the aircraft mentioned above, the pilot can revert to controlling the aircraft manually should the automation fail. In certain classes of automated aircraft, however, this is no longer possible, because the aircraft is inherently unstable and therefore some level of automation is required at all times. One example are the experimental Control Configured Vehicles (CCV's), which require control inputs on a second-by-second basis to respond to rapidly fluctuating aerodynamic forces; manual

control of these vehicles is impossible. NASA's Space Shuttle is another example. In such aircraft, multiple redundancy is built in to the automation to minimize the risk of system failure (e.g., the Space Shuttle has four (redundant) flight control computers on-line simultaneously as well as an off-line backup).

Automation in military aircraft has followed a roughly similar path to that in civilian automation, with some differences. A comparison of older and modern military aircraft will reveal many superficial similarities to civilian automation trends. For example, an older-generation fighter such as the F-4 had numerous lights, knobs, dials, and other simple display and control devices in place of the multifunction CRTs of modern tactical aircraft. However, there are important differences between the two spheres of aircraft automation in a few areas related to the special functional requirements of military aircraft (e.g., targeting and weapon deployment). The time critical nature of flight functions in fighter aircraft has also imposed special requirements unique to military automation. Finally, automation trends have also been more rapid in the civilian than in the military sector because of the time delays inherent in funding, procurement, testing, etc.

In general, aviation automation has progressed from (largely) mechanically-based systems to computer-based systems incorporating machine "intelligence". As a result, the functionality made available by automation has advanced from very limited systems to highly flexible systems in which the functionality of the automation may be chosen according to the user's needs. A case in point is the increasing number of modes and options available in the modern, state-of-the-art autopilot. However, the case studies into accidents involving modern aircraft have suggested that such diversity of function also imposes costs in terms of operations complexity from the pilot's standpoint. As a result, designers have had to ask if in fact systems with total flexibility are in fact desirable?

Aircraft Automation: Benefits and Problems

Aircraft automation has provided important benefits in a number of areas, including fuel economy, flight control, and navigation. The extent of automation technology development and the significance of these benefits have been such that the era of automated aircraft is well established---there is no turning back. But along with these benefits, there have been some problems. The problems have been not merely those normally associated with the introduction of any new technology, but fundamentally new problems. It has been increasingly recognized, for example, that while aircraft automation has reduced or eliminated many kinds of error, it has also introduced new forms of error that did not exist previously (Wiener & Curry, 1980). Many pilots have negative reactions to automation because they feel it has increased rather than reduced mental workload (Wiener, 1985, 1987). Automation sometimes has had negative effects because the resulting human-machine interface is altered in unpredictable ways (Adler, 1986; Hirschhorn, 1984; Noble, 1984). On a more mundane yet nevertheless important note, automation of some operations may not

produce expected improvements because of excessive downtime for repair and calibration (Blumenthal and Dray, 1985). In an extensive evaluation of trends in commercial aviation, Norman et al. (1988) reached three major conclusions concerning the development of aviation automation : (1) The use of automation has been incremental in nature. (2) The use of technology has resulted in the partial alienation of the pilot. (3) New errors have been introduced with the use of new technology. The impact of automation on the pilots is poorly understood in part because of how it has been implemented in present day systems.

Developments in CRT technology, expert systems, and parallel-distributed processing have made it possible to automate many high-level functions in aircraft. As a result, the major issue that has arisen is not so much whether one should automate, but what functions should be automated and when (Wiener & Curry, 1980)? Better implementation of new automation requires an understanding of how automation can be optimized, that is, how to get maximum benefits from using automation while correcting all possible errors that may emerge as a consequence of its implementation. The pilot's view of "good" automation is represented by Hoagland (1984), who suggested that in such a system the pilot can still have some role to play during critical phases of an automated flight. To achieve this, important information for the pilot is needed. Hoagland attributed the occurrence of several errors in automated aircraft to bad system design and to the tendency of manufacturers to accept any request to automate. Manufacturers have apparently followed the strategy of automating where possible (i.e., when the technology allows it). The apparent conflict between the manufacturers' interests and the goals of good human factors design needs to be bridged. Consideration of this issue requires an analysis of the benefits and problems associated with automation.

Benefits of Aircraft Automation

Boehm-Davis, Curry, Wiener and Harrison (1983) distinguished between two types of automation benefits. One kind of advantage accrues because the automation carries out functions that cannot be achieved otherwise either because humans cannot perform them or because of problems of cost, safety or time needed to achieve such functions manually. For example, automation has allowed aircraft to fly in all weather conditions in a safer manner. In modern tactical fighters, automation is necessary to help the pilot cope, particularly under conditions of time pressure, with an increasingly complex threat environment. A second type of benefit offered by automation occurs because automatic systems provide better performance than humans.

These kind of benefits can be perceived from two points of view. From a human standpoint, these benefits are expressed in such terms as decreased pilot workload, easier aircraft handling, increased safety, increased passenger comfort, better schedule dependability, and so on. For example, automation has reduced cockpit crew size in commercial aircraft by one-third without increasing workload significantly for the

remaining two crew members (Norman et al, 1988). Reduced crew size (without reduced system performance) is also a significant benefit from a systems viewpoint. Given crew training costs for advanced tactical aircraft, this represents a significant benefit. Other system benefits of automation include consistency, reliability, and cost-effectiveness. Aircraft automation has decreased fuel consumption, reduced flight times, and has made possible operations in virtually all weather conditions. These are significant advantages given the rapid rise in air traffic and the increase in fuel costs in the last two decades.

In military aviation, automation has conferred the above-mentioned benefits as well as others, such as improved flight performance, expanded tactical capability, and reduction of peak periods of pilot workload. Pilots of modern fighter aircraft fly in such a high-workload environment that they would be overwhelmed at certain critical times in the flight without the assistance of automation. This last feature is unique to automation in military aircraft. It also raises a potential problem that leads to the issue of the costs associated with automation that is discussed in the next section. Given the high workload levels that the fighter pilot has to contend with, even relatively minor functions may have to be automated for no other purpose than to keep pilot workload at manageable levels and to enable the pilot to concentrate on the more important, time-critical functions (McDaniel, 1988). While this may be an effective automation strategy is some instances, it could also lead to certain difficulties for the pilot.

Problems of Aircraft Automation

Aircraft automation has not been without its unique problems, above and beyond simply the "teething" problems associated with any new technology.

Automation-induced problems. This type of problem arises when the anticipated benefits that automation is expected to confer (such as those mentioned above), do not occur. One example of such *violations of anticipated automation benefits* occurs when the pilot is faced with greater workload levels with an automated system than existed prior to the automation, despite the fact that the automation was intended to reduce workload. McDaniel (1988) described how this problem can occur in the context of fighter aircraft automation:

> "If the automation of a critical function is not perfectly reliable, the pilot will need to monitor it in order to intervene quickly should a malfunction occur. If the pilot continuously monitors the automation, he can intervene in about one second. If he is attending to another task when the malfunction occurs, the reaction time will be several seconds because he must also refresh his awareness of the situation as well as detect that a malfunction has occurred, what has malfunctioned, and what to do about it. In many situations, the malfunctioning aircraft cannot survive even those few seconds. As a result, a pilot dares not perform a second non-critical task rather than monitor the automated critical task. So, while this type of automation permits a useful task to be

accomplished, it does nothing to free the pilot's attention resources for other tasks." (p. 837).

The paradox is that implementing automation in an attempt to reduce workload may actually result in increased workload, because of the cognitive workload associated with monitoring the automation. This increased workload can be a problem which may lead to major difficulties in certain situations. Boehm-Davis et al. (1983) also identified *passive monitoring* as a related, potentially important category of an automation-induced problem. In highly automated systems, the pilot may be relegated to the role of a passive monitor, a task for which humans seem ill suited (Parasuraman, 1987; Wiener, 1987). As a passive monitor, the human operator's function is simply to observe the operation of the automated system, with no expectation, or capacity, to affect its operation. Such a role is not a stimulating one and may lead to boredom or complacency, as well as to possible inefficiency in the event of the need for manual control under emergency conditions (Parasuraman, 1987). Automation may also induce problems because of training inadequacies with respect to monitoring. Training needs for automated systems are complicated because users need to be trained as monitors for situations when the system is fully automated and as controllers when the manual mode is on. The skills required for both capacities may conflict with one another, making it difficult to decide where to place priorities during training. Training issues are considered further in a later section of this report.

Another example of an automation-induced problem is the ground proximity warning system (GPWS) which produced many false alarms when first implemented in the cockpit. When automation does not function properly, it creates additional problems of *credibility*. Users' trust of a particular system is based on past experience with such systems as well as their knowledge of its accuracy. If, for instance, pilots are unsure or skeptical of the reliability of an automated system they may not use the system effectively.

Problems resulting from technology-centered design. These concern those problems that arise as a result of the failure of system designers to consider the role of the operator of automated systems. One major problem that technology-centered automation design is thought to have led to is the *peripheralization* of the pilot. Some examples related to peripheralization of the pilot can be summarized as follows (Norman et al, 1988): 1) Loss of situation awareness, in which the pilot does not have an adequate, up-to-date model of the relationship of his aircraft to the tactical airspace around him. 2) Loss of system awareness, in which the pilot is usually unaware of the system capacities and limitations as well as its behaviors in specific situations. 3) Poor interface design. A good example of this type of complication is the reprogramming of the flight management system to adapt to any change during the approach phase. This phase represents such a high workload level for pilots that they usually turn the automatic system off and use a manual approach. 4)

Loss of manual skills. Most pilots of highly automated aircraft often manually fly their aircraft because of a fear of losing their basic flight skills (Curry, 1985; Wiener, 1988).

It is now well recognized, at least in human factors circles, that these problems are not unique to aircraft systems, but have arisen in several other systems in which automation has been implemented without sufficient regard for the needs and characteristics of the user of the automated system (Woods, 1988). This problem has been attributed to what is called *technology -centered automation*, in which the system is primarily designed as a function of the capabilities of the available technology. The alternative that has been proposed to technology-centered design is *human-centered automation* (NASA, 1989), an approach that attempts to take into account user requirements in the design process. This approach, and its application to the design of adaptive automation, is considered later in this paper.

Effects of Automation on Human Performance

Only a few empirical studies have been carried out to evaluate the effects of automation on human performance. The strategy that most studies have followed is to compare performance of tasks under automated conditions to that under manual conditions. This raises an immediate difficulty. Automating a function in a complex system such as the cockpit changes the nature of the tasks the pilot faces, so that a comparison between automated and manual performance involves a number of different variables, not all of which can be easily controlled. One approach to dealing with this problem is to examine manual performance of only a single important piloting task, such as system monitoring (e.g., failure detection) as a function of whether other tasks are executed manually or automatically.

Effects on System Monitoring

As discussed earlier, automation may have adverse effects because it places the pilot in the role of a passive monitor. Wiener (1988) has given a number of examples of accidents in which monitoring failures in automated cockpits were a major contributing factor. In contrast to passive monitoring, crew members actively involved in monitoring are expected to have more knowledge of the system and "more practice at a knowledge-based level of behavior" (Idaszak and Hulin, 1989), and thus be better equipped to detect a system failure. While this reasoning is eminently plausible, only a few studies have attempted to provide empirical evidence in support of this view.

Wickens and Kessel (1981) carried out a study in which subjects had to either , 1) monitor only , or 2) both monitor and control, a tracking task. The monitoring task involved a sudden change in the control system dynamics; this represented the "failure" that the subjects were required to detect. In the "manual"

condition subjects actively controlled the tracking and monitored at the same time. In the "passive automation" condition subjects only monitored the system dynamics. Speed of failure detection was found to be significantly slower in the automated than in the manual condition. This result was attributed to the subjects' having a better mental representation of the system dynamics in the manual mode (through visual and kinesthetic feedback) than in the automated mode.

Idaszak (1989) carried out a related study using a simulated process control task. Subjects were required to monitor the system and respond to limits, alarms, and deviations in process parameter values. In the active monitoring condition subjects controlled the process and monitored it at the same time. In the passive condition, subjects only monitored the process while watching a video of nature scenes. Idaszak (1989) found that the active group monitored better than the passive group: active operators were faster at detecting both out-of-limits conditions and alarms than the passive operators. Idaszak and Hulin (1989) suggested that active participation increases the operator's workload and perceptions of task difficulty ,and therefore, active participation acts as a source of motivation, and benefits monitoring performance. However, one problem with this study is that the passive group was required to answer questions about the video they watched; hence it is likely that they were forced to allocate resources away from the monitoring task, and this diversion of resources may have been greater than in the active group doing both the monitoring and the controlling task. It is therefore questionable whether the passive condition used in this study is representative of the passive monitoring that automation in the cockpit induces.

These results provide some empirical support for the contention that automation impairs manual monitoring performance under emergency conditions, a so-called "automation deficit" (Wiener & Curry, 1980). However, the studies are by no means conclusive in demonstrating such a deficit. Moreover, more needs to be learned about the characteristics of this deficit. Is it a general phenomenon affecting all aspects of cognitive performance? What is the minimal level of manual involvement required for the deficit not to occur, and what cognitive processes are involved? The evidence available to date suggests that the phenomenon may not be a very general one and may only occur in continuous tracking tasks. Fuld, Liu, and Wickens (1987) carried out an experiment that was designed similarly to that by Wickens and Kessel (1981), but involved a continuous visual sorting and queuing task instead of a tracking task. Subjects had to assign an incoming "customer" to one of three queues for service. In the manual mode, subjects had to make assignments (by pressing one of three buttons, one for each queue) as well as monitor their own assignments and press another key if they detected an error. In the automated mode subjects were told that the queuing assignments would be made by the computer and that their task was only to detect wrong assignments. In fact, the 'automation' condition was simulated by giving each subject a replay of their earlier manual performance; this was done to control for visual display differences between the automated and manual modes. Fuld et al. found that, in contrast to Wickens and Kessel (1981), monitoring performance

(sensitivity (A') in detecting wrong assignments) was better in the automated condition than in the manual condition. However this effect may have been influenced by the control method that Fuld et al. used. Because subjects performed the automated condition *after* the manual condition and received the same sequence of stimuli, they may have benefitted from seeing difficult errors (that they made initially in the manual condition) again in the automated condition, whereas subjects seeing such errors for the first time may not have detected them.

Effects on Situational Awareness

Kibbe and Wilson (1989) conducted three experiments examining the effect of automation on the retention of information from cockpit displays. A simulated electronic warfare (EW) display was used in each study, incorporating a threat detection task and a tracking task. Subjects were queried at the end of a scenario on various aspects of the threat detection task, as an indirect measure of their "situation awareness." Kibbe and Wilson hypothesized that automation impairs situational awareness because the operator is not actively involved. Manual and automated modes of performance were compared to test this hypothesis. While a number of expected results related to single versus dual-task performance were obtained, there were no significant effects of system mode (automated or manual) on the amount of information retained from the display. Thus the experiment failed to find any effect of automation, positive or negative. A minor finding was that some subjects intervened more than others in the automated system and switched to the manual mode when the automation failed. This behavior (intervention) was not linked to any changes in the performance of either one of the two tasks.

Relative Costs and Benefits of Automation

One of the few empirical evaluations of the relative merits and costs of automation technology with respect to pilot performance was carried out by Bortolussi and Vidulich (in press). A helicopter simulation was designed to examine the interaction between voice-activated controls and altitude-hold automation. Pilots conducted simulated missions which included hover, cruise and ground attack phases. Voice-activated controls were used instead of manual controls for half of the flights (for weapon selection and data-burst transmission). Results showed that voice-activated controls helped improve hover performance during data-burst hover. This improvement was interpreted as an outcome of a small reduction in the competition for manual resources. On the other hand, and as indicated by the pilot's subjective rating, pilots preferred manual control activation for high priority flight tasks, such as weapon selection. The pilots reported that workload increased while using voice-activated controls, primarily due to their unfamiliarity with the systems and their reliability. The altitude-hold automation improved performance on tasks and pilots reported low

workload. However, pilots were significantly slower in responding to unexpected events during hover. This was interpreted as a significant cost associated with automation. Note that this "automation deficit" effect, like that of Wickens and Kessel (1981) again involved a tracking task. Further research is needed to determine whether this effect is indeed restricted to tracking or motor tasks, or whether it is a more general phenomenon.

Adaptive Automation Concepts

While automation has offered new techniques to solve various problems encountered in advanced aircraft, it has brought new questions about the role and and effectiveness of the pilot. At the same time, as indicated above, the benefits associated with automation have been accompanied by certain costs. It has been proposed that one reason that aircraft automation has led to certain difficulties is because existing approaches to automation implementation have been "static" rather than "dynamic" (NADC, 1989). In this view, it has been proposed that many of the benefits of automation can be maximized and the costs minimized if automation is implemented in an adaptive manner rather than in an all-or-none fashion (NADC, 1989; Rouse, 1988). But this approach to automation has yet to be demonstrated reliably, either in the laboratory, simulator, or cockpit. More research is required to test the concept, and, most importantly, to acquire *empirical evidence* for its effects on pilot and system performance.

Adaptive processes are thought to allow synergistic communication between the pilot and the support automation. For example, the pilot can actively control a process during moderate workload and allocate this function to an automated subsystem during peak workload if necessary. Fully, or statically automated processes, on the other hand, can impact negatively on pilot workload and lead to a loss of system awareness (Norman et al., 1988). Adaptive automation is thus believed to allow the advantages of automation to be realized while maintaining pilot involvement in the system. Currently ongoing research at a number of laboratories will determine whether this assertion is true.

The adaptive automation concept is not a new one, having been proposed several years ago (Rouse, 1976). The idea of automation that is variable rather than fixed also falls naturally out of the "levels of automation" concept discussed earlier. It is also related to the classic problem in human factors of allocation of function between humans and machines (Fitts, 1961; Jordan, 1963; Parasuraman, 1990; Singleton, 1971). Usually the decision as to which operations should be carried out by computer is determined by whether automation is feasible or not. Because decisions about task allocation cannot always be made based on stereotypical characteristics of human and computer capabilities, the need for an adaptive computer aid that responds to task demands and operator performance becomes a logical design alternative for increasing

system effectiveness (Hancock et al., 1985; Morris, Rouse and Ward, 1984). While previous attempts to solve the allocation of function problem met with mixed results (e.g., see Jordan, 1963), developments in computer technology, particularly in machine intelligence and parallel-distributed processing, have led to greater optimism for the success of adaptive systems.

In addition, the emergence of expert system technology has facilitated the development of systems design tools that allow a better understanding of the operator (expert) decision process. Given a greater understanding of the strategies and knowledge of the pilot, it should be possible to design adaptive automation that can work *with* as opposed to *for* the pilot.

At the moment, however, adaptive systems provide only a promise for an improved pilot-vehicle interface; whether that promise is realized will depend first upon the satisfactory resolution of a number of issues related to the methods by which adaptive aids are implemented. Furthermore, it is important that these issues inform the design methodologies that are used in actually building adaptive automation into the cockpit. In the final section of this paper some prospective design principles are discussed. Finally, other issues such as user acceptance and the ease of use of adaptive aids, which may appear ancillary at first, may also ultimately determine the success of adaptive systems. As Rouse (1988) put it: "When we first introduced the (adaptive automation) concept to aircraft pilots in 1974-75 their comments ranged from thoughtful cautions to outright ridicule. More recently (1987)....., we have found pilots to be *quite positive* but still conservative" (p. 442).

One of the key issues in adaptive automation concerns the method by which adaptation is implemented. In other words, how is the adaptation to be done? What properties (of the pilot, the task environment, or both) should the adaptive logic detect and respond to? What tasks should in fact be automated, and when? A number of different schemes for adaptive task allocation have been proposed, from methods based on dynamic measurement of operator workload or psychophysiological states to optimal performance models that incorporate rule bases on operator resources, strategies and intentions (Hancock et al., 1985; Parasuraman & Bowers, 1987; Reising, 1985; Riley, 1987; Rouse, 1977; Rouse & Rouse, 1988). These automation control strategies are considered next.

Adaptive Automation Control Methods

A number of proposals for adaptive systems have been proposed over the years. Rouse (1988) has categorized all adaptive schemes as based on either *measurement* or *modelling* of the operator. However, a third category for invocation of adaptive processes, based purely on mission doctrine, is also possible. This

method is called *critical-event logic* and can be implemented without the need for measuring or modelling the pilot's performance (Barnes & Grossman, 1985). All three methods are considered in more detail below.

The advantage of critical-event logic is that it can be tied closely to actual military tactics and doctrine. Its disadvantage is its insensitivity to actual pilot performance or workload. The measurement technique attempts to overcome this limitation. In this method, various pilot mental states (workload, vigilance, strategies, intentions, etc) may be measured and these measures then fed to some adaptive logic. Alternatively pilot states and performance may be modelled theoretically, with the adaptive algorithm being driven by the model parameters.[5] The measurement and modelling methodologies each have merits and disadvantages. Measurement has the advantage of being an "on-line" technique that can potentially respond to unpredictable changes in pilot cognitive states. However, this method is only as good as the sensitivity and diagnosticity of the measurement technology. Modelling techniques have the advantage that they can be implemented off-line and easily incorporated into rule-based expert systems. However, this method is only as good as the theory behind the model, and many models may be required to deal with all aspects of pilot performance in a complex task environment. Hybrid systems that combine measurement and modelling, or critical-event logic and measurement, or other possible combinations of these methods, may optimize their relative benefits.

The adaptive scheme that is simplest conceptually, and relatively easy to implement is one employing critical-event logic. An adaptive scheme that is also simple conceptually, but not necessarily the easiest to implement, is one based on assessment of operator workload. An operator workload based system has appeal because the primary raison-d'etre for adaptive automation is the regulation of mental workload. Assessment of the pilot may also extend to psychophysiological states. These are both measurement methods. Finally, optimal performance models of the pilot may also be used as the basis for adaptation. We discuss each of these methods in turn.

Critical-Event Logic

In this method the implementation of automation is tied to the occurrence of specific tactical events (Barnes & Grossman, 1985). For example, the beginning of a "pop-up" weapon delivery sequence may lead to the automation of all aircraft defensive measures. This method of automation is adaptive because if the critical events do not occur, the automation is not invoked. Such an adaptive automation method is inherently flexible because it can be tied to current military doctrine during mission planning.

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[5] For example, model-based adaptation is used in the Pilot's Associate.

Barnes & Grossman (1985) identified three types of adaptive logic within this general scheme: (1) *Emergency logic*, in which a control process is executed without pilot intervention initiation or intervention (for example, SAM detected within critical envelope). (2) *Executive logic*, in which the subprocesses leading up to the decision to activate the process are automatically invoked, with the final decision requiring the pilot's input. (3) *Automated display logic*, in which all non-critical display findings are automated to prepare for a particular event, so that the pilot can concentrate on the most important tasks. Interestingly, this last method is also implicitly a workload-related method, although it is not workload-*adaptive*, because it assumes that the pilot's workload will always increase beyond his upper limit when the critical event occurs.

To be successful, systems based on critical-event logic would require an intelligent interface to allow the pilot to set up tailored rule bases before the mission. Similar, although simpler, adaptive methods are currently implemented for AEGIS and the HARM missile system. The AEGIS system is based on doctrine which the ship commander sets for the current operational environment. Doctrine is a small rule base in a production system that determines how the AEGIS system will operate in a combat environment. Three modes of operation are implemented: (1) Manual, where the system is fully controlled by the operator. (2) Automatic special, in which a critical event (e.g., an enemy aircraft at a specified range) would automatically set up a weapon-delivery process (e.g., prepare standard missile to fire); however, the operator would press the fire button;. (3) Fully automated, where the need for a short reaction time requires automatically involving ship defensive systems without operator intervention (Armageddon).

The problem with these systems is that they are relatively unsophisticated and are unresponsive to actual operator workload or performance. It is even possible that their rule bases have unforeseen, interactive consequences in a complex environment. In both the automatic-special and fully-automated systems, the rule base is kept small and decidedly "non-expert" to allow the planner to understand the consequences of the rules. The operator workload is reduced because decisions can made off-line prior to combat. At the same time, the user (based on local conditions) and an AI "expert" tailors the rule base controlling the adaptive logic.

In conclusion, adaptive automation based on critical-event logic probably represents the "baseline" adaptive system. These systems are simple and relatively unsophisticated by design. Important measurement and modelling problems must be overcome before such adaptive systems can be controlled by truly intelligent logic.

Dynamic Assessment of Pilot Mental Workload

Rouse (1977) first described a conceptual scheme for dynamic allocation of tasks in a multi-task situation based on the operator's moment-to-moment level of workload. Mental workload-based methods of adaptation lie at the heart of the basic rationale for implementing automation in an adaptive rather than fixed manner. The goal of adaptive automation is to regulate pilot workload levels around some optimal level that is neither too low nor too high. Critical to workload-based adaptation is the availability of a reliable assessment of pilot mental workload obtained in real-time (second-to-second or minute-to-minute, depending upon the specifics of the mission). The development of accurate, non-obtrusive methods for assessing workload and incorporating them into real-time algorithms is essential if workload is to serve as the basis for determining what functions are to be automated and when.

Operators of complex systems such as fighter aircraft generally work in a very high workload environment. However, automation of a function may be useful or even essential to the pilot at one moment but not at another. Workload levels fluctuate from moment to moment and at different mission phases. Pilots may be able to achieve very high performance levels but only at the cost of high mental workload and, perhaps, the neglect of less critical tasks. As a result, if this high level of workload has to be sustained for long periods of time, performance degradation may result. Alternatively, performance may deteriorate with the addition of other minor tasks. Furthermore, different pilots will use differing strategies to cope with the demands of multiple tasks under time pressure, which will require the development of custom tailored adaptive automation algorithms if the system is to be compatible with, and complement, the strengths and weaknesses of individual pilots. Moreover, individual differences in pilot capabilities will influence the response to multiple task demands--the superior pilot will have sufficient resources left to cope with other tasks whereas the average pilot will be operating at peak workload. Hence any "static" automation system scheme that implements automation on the basis of the required workload demand on an average pilot will penalize and consequently underutilize the skills of the superior pilot.

For each of these reasons, an automation scheme that is responsive to individual, momentary workload levels, will serve to regulate workload and optimize performance regardless of specific tactical demands and pilot capabilities. Note that *workload* is adapted to, not *performance* (although a performance measure may be used to assess workload). Given that the technical problem of dynamic workload measurement can be solved, adaptive systems should achieve the goal of optimal mental workload to be pursued in dynamic, real-time environments.

Sensitivity and Diagnosticity. The efficacy of workload-based adaptation is dependent upon the sensitivity and diagnosticity of the workload measurement technology[6]. The research literature on workload measurement techniques has grown to voluminous proportions in recent years (Hancock & Meshkati, 1988; Moray, 1979; Wickens, 1984). A number of sensitive measures have been identified, with the most reliable measures being based on variations of the secondary-task method. Other categories of workload measurement technology involve primary-task measures, psychophysiological indices, and subjective measures. However, it has proved more difficult to find measures that are both sensitive to momentary fluctuations in workload and can be implemented easily in the cockpit.

In addition to sensitivity, a workload metric must be diagnostic to be of use in adaptive automation (Wickens, 1984; Wickens & Kramer, 1985). In other words, the measure must indicate what component of mental workload is under or over-stressed. For example a pilot heavily loaded with visual display information may nevertheless be able to cope effectively with auditory inputs. A workload method that did not provide some measure of diagnosticity may therefore erroneously trigger the adaptive algorithm to off-load the pilot. Unfortunately, while considerable progress has been made in developing sensitive workload measures, there has been less progress in developing h'ghly diagnostic workload measures.

Dynamic Aspects of Workload. Hancock and Chignell (1988) have recently proposed a workload model in the context of adaptive systems. In contrast to most existing approaches to workload, which tend to be "static" and driven solely by task structure (e.g. display and response modes), their model is a dynamic one which recognizes that operators pursue active strategies to regulate their workload in response to task demands. Such regulatory strategies include, pre-planning, task scheduling, and partial task postponement. The time available for carrying out functions in a multitask situation plays an important role in their model. According to Hancock and Chignell, "successful performance depends upon the reconciliation of the complexity and difficulty of the imposed task with the time within which the goal must be achieved" (p 649). Their hypothesis is that task-induced mental workload is a joint function of the current subjective distance from a desired goal, the real time needed to reach that goal, and the level of operator effort required to achieve the goal, given the time available. These three factors can be represented in a three-dimensional surface by which momentary workload c be assessed. Hancock et al. (1989) carried out an experimental test of the model using a target acquisition task (i.e. a Fitts' Law task) with targets that varied continuously in

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[6] A number of other workload-measurement criteria are also relevant to adaptive automation, including the intrusiveness of the method, its acceptability to the pilot, etc. See Eggermeir and O'Donnell (1986) for a discussion.

size. Performance measures and subjective workload indices gave generally good fits to the predictions of the model.

The adaptive aspect of Hancock and Chignell's (1988) model is similar to other adaptive automation schemes. Adaptation (task loading, task automation, task aiding, etc) requires an evaluation of both demands on workload and the available operator resources. In Hancock and Chignell's scheme, this could be achieved using either measurement or modelling (which they term as prediction). Once information about the level of mental workload is provided, the adaptivity of the system may be tailored to the needs of a human operator. They suggest that the first step is to develop a criterion for adaptivity. This is accomplished in two stages: (1) Estimating how far workload is (lower or higher) from the optimum;(2) Generating a diagnosis of information so as to evaluate the load on particular cognitive structures.

The proposed model works as follows: first the task is defined, structured and subtasks allocated to either an automated subsystem or to the operator. Next, the operator's effort is compared with the task difficulty so as to assign a criterion for adaptivity. The criterion can be expressed as a measure of mental workload, a measure of primary task performance or a combination of both. Once the criterion is defined, an adaptive policy is implemented. In other words, the criterion remains dynamic and changes every time there is an alteration in the operator's performance and/or task complexity. The adaptive system is defined as alteration of task components in order to improve future measures of the criterion. In other words, the adaptive system's role is to minimize the difference between present requirement and accessible capacity. Adaptivity, according to this workload-based measurement method, can be achieved through three main procedures: by adjusting the allocation of subtasks between the operator and the automation; by adjusting the structure of the task; and by redefining the task.

Dynamic Psychophysiological Assessment

Psychophysiological states of the pilot may provide additional information that can be tapped for control of adaptive systems. Technology is available to measure a number of physiological signals from the pilot, from autonomic measures such as pupillary dilation (Beatty, 1986) and heart rate (Jenkins, 1986) to central nervous system measures such as the EEG and event-related potentials or ERPs (Donchin, Kramer, & Wickens, 1986; Parasuraman, 1990), as well as measures such as eye scanning and fixations . There is now a substantial literature indicating that different psychophysiological measures can be obtained of such covert mental activities as attention allocation, memory look up, and response preparation. However, given the greater cost and unproven reliability of psychophysiological measures in the cockpit, it is pertinent to ask why they should be used. What advantages do psychophysiological measures offer over behavioral methods, if any?

Psychophysiological measures offer two main advantages over other measures. In certain applications, these advantages may be sufficiently high to overcome the disadvantages of cost, user acceptance, etc. associated with these measures. First, psychophysiological measures, unlike most behavioral measures (with the exception of tracking error) can be obtained continuously. In many systems where the operator is placed in a supervisory role, very few overt responses (e.g. button presses) may be made even though the operator is engaged in considerable cognitive activity. In such a situation the behavioral measure provides an impoverished sample of the mental activity of the operator. Psychophysiological measures, on the other hand, may be recorded continuously without respect to overt responses and may provide a measure of the covert activities of the pilot. Second, in some instances, psychophysiological measures may provide more information when coupled with behavioral measures than behavioral measures alone. For example, changes in reaction time may reflect contributions of both central processing (working memory) and response-related processing to workload; however, when coupled with P300 amplitude and latency changes, such changes may be more precisely localized to central processing stages than to response-related processing (Donchin et al., 1986).

How would a psychophysiologically based adaptive system work? It is presumed that pre-existing "profiles" can be established for each pilot indicating the correspondences between a specific pilot state (such as reduced vigilance, increased workload, etc) and the measured physiological signals (*e.g., see* Carriero, 1977). A psychophysiological adaptive system would assess these states "on-line," feeding this information to a secondary logic system (e.g., an expert system) that would determine whether adaptive changes are required. This concept is not new, having first been proposed in the context of a program funded by DARPA in the 1970's for a "biocybernetic communication channel" between pilot and aircraft (Donchin, 1980; Gomer, 1980). Hancock et al. (1985) reported a more recent proposal in which physiological signals would be coupled to an intelligent subsystem that implements adaptive functions such as task allocation.

Various candidate psychophysiological measures are available, most of which can be drawn from the literature on physiological measures of workload. Probably the most widely supported measures are those based on brain electrical activity, and in particular the P300 and N100 event-related potentials of the brain (Donchin et al., 1986; Parasuraman, 1990). Both these ERP measures have been shown to provide a fairly sensitive measure of mental workload in multi-task situations. In addition, these brain potentials have a measure of diagnosticity as well. The P300 has been shown to reflect primarily the allocation of perceptual-cognitive resources and not response-related processes (Donchin et al., 1986). The N100 brain potential, on the other hand, has been found to reflect attentional resources associated with early information-processing stages (Hillyard & Kutas, 1983). Of the autonomic measures, heart rate variability, and particularly

in the 0.1 Hz frequency band, has been reported to be a sensitive index of momentary workload. This measure has the advantages of requiring simpler instrumentation than ERPs. However, heart rate variability may be less diagnostic a measure than ERPs, and may reflect a number of different sources contributing to workload.

Several critical conceptual and technical issues must be tackled before psychophysiological adaptive systems could be fielded. The criteria of sensitivity and diagnosticity that apply to behavioral workload measures apply equally forcefully to psychophysiological measures. In fact one could make the argument that the sensitivity issue applies more stringently. This is because it is generally possible to attach some meaning to absolute values of behavioral measures, even with only limited knowledge of the stimulus context. For example, a reaction time of 200 msec or an accuracy score of 95% can be taken to represent highly efficient performance. The meaning of a P300 amplitude of 15 µV, on the other hand, cannot be determined without details of the experimental and recording conditions. Major technical problems (e.g. artifact-free recording in noisy cockpit environments; reliable single-trial recordings, etc.) have to be solved before psychophysiological measures could be used routinely in aircraft. In addition, factors such as reliability, cost, and pilot inconvenience and mistrust, must be dealt with. A great deal of technical development must be devoted to psychophysiological methodologies before they could be seriously considered for fielding in airborne adaptive systems.

Pilot Performance Models

Pilot performance models are important to the design and study of automation issues because they provide the basic framework with which to understand pilot behavior. As such, the adoption of an appropriate pilot performance model is going to be critical to the successful development of an automation system, because the assumptions implicit to a model will carry through to affect the way in which the automation system is designed. Further, the pilot performance model is going to be even more critical in the development of adaptive automation systems because the very complex interaction between the pilot and the automation system will change substantially as a function of the level of automation, and the shifting levels of automation will in turn be affected by the model. The advent of adaptive automation therefore makes the issues associated with the pilot performance model more critical, as they will impact both the pilot's performance as well as the researcher/designer's understanding of it. This section of the report will describe some of the current and/or more promising models of human performance which hold promise in attacking the problems of adaptive automation in the cockpit.

Pilot measurement methods have some inherent limitations. They may be too sensitive to small local fluctuations in pilot workload or physiological states, measurement technologies may be costly, impractical or intrusive (e.g., particularly for physiological measurement), and pilots may be unwilling to accept being "monitored" in the cockpit. An alternative to measurement is to model the performance of the pilot and to base adaptation on features of a given performance model. Several optimal performance models for adaptive systems have been proposed. A number of information-processing models of human cognition are also relevant, although these were not specifically developed in the context of adaptive systems. We consider three such categories of models which seem to have the most promise in application to adaptive systems.

Intent Inferencing Models. A major advantage of the modelling approach is that several pilot models can be incorporated into the adaptive aiding system in the cockpit. For example, a data base of tasks and a rule base for assessing workload in different task configurations can be developed. Alternatively, a rule base linking operator intentions to specific responses can also be used. These will permit the adaptive system to acquire knowledge about operator actions. This knowledge is useful for the computer to adapt to the intentions of the human operator. Rouse, Geddes, and Curry (1986) stated that the goal of performance models is to allow the adaptive system to evaluate the operator's : (1) present goals, as well as present and future behavior; (2) efficiency in performing a task; (3) situational awareness; (4) available information-processing resources; and (5) planned goals and actions.

Intent inferencing models may allow these goals to be realized. In this kind of model, available pilot resources and performance are used as predictors to decide when to let the intelligent aid intervene. Intentions can be represented in a number of ways, although script-based representations have been most commonly used. Examples of intent inferencing models are those of Geddes (1985), Greenstein & Revesman (1986), and Govindaraj & Rouse (1981). These two last models characterize human intentions as responding to task requirements. That is, humans could not have any goals besides those imposed on them by task demands. Such an assumption may be violated in certain operational settings (Geddes, 1985). Geddes included in his model the interpretation of human actions, the system state, and the state of the world in the context of scripts, plans and goals. His model acknowledges the existence of human thoughts, personal goals and consequently human intentions which are not specifically related to the context of task demands. It remains to be seen whether script-based representations can capture all aspects of pilot intentions and goals in the complex environment of the fighter aircraft.

Optimal (Mathematical) Models. Examples of optimal models include those based upon signal detection theory, information theory, queuing theory, sampling theory, and control theory. Each of these theories offer context-free representations of normative human performance in tasks that can be related to

task components in various operational domains. Queuing theory is considered here as an example of such models. This model is chosen from the many available models because its range of applicability is quite broad. The reader interested in other mathematical models of human performance can refer to Sheridan and Farrell (1974) and Rouse (1980).

Optimal control models such as that of Baron and Levinson (1980) focus on the prediction of human control dynamics under various load conditions. Models of instrument scanning (monitoring) based on sampling theory (e.g., Moray, 1984) have also been proposed. Pilots are clearly engaged in both these activities, as well as other decision-making and planning activities. A general mathematical model that can be applied to this multitask situation is queuing theory. The queuing model proposed by Walden and Rouse (1978) was developed in response to the limitations of some of the previously-mentioned models as well as to meet the requirement for computer aiding schemes for pilot multitask performance. Their model focused on time sharing between monitoring, flight control, and other tasks. The model considered the monitoring task as a queuing system which can be modeled as a "single server" with subsystem events called "customers" and with the control task incorporated as a special queue. The system, according to this model, works as follows: Once the customers arrive at the control task queue they can control the service of a subsystem event. From what preceded, a customer in this case can be defined as a "significant amount of display error". Therefore, when a major error is displayed, the subsystem service is preempted and a control action is taken to eliminate the error.

To demonstrate the usefulness and workability of their model, Walden and Rouse (1978) conducted an experiment to study performance in a simulated multitask flight management situation. Two independent variables were manipulated, the inter-arrival times of customers and the level of difficulty of the flight path to be followed by the pilot. The goal behind this study was to compare the effects of automated versus manual control on system performance. Subjects were tested in two sessions, a training session for the monitoring task, and a test session in which subjects performed under automation (with autopilot failure). The independent variable was inter-arrival times (30, 60 and 90 sec. per subsystem). Dependent variables consisted of reaction time to the subsystem event and the time spent for the diagnosis of the event. An easy terrain map was given to subjects for the first trial of a session . The second trial consisted of a more complex map. A single control task was used in the first session so as to establish baseline performance. The rest of the trials involved the three levels of monitoring workload. Dependent variables in the second session involved the two measures mentioned earlier as well as aircraft position and attitude and finally pilot control inputs.

The results from this study showed that subjects usually "smoothed" the version of the designed map to follow a simpler and more realistic map by adopting a "mental smoothing procedure" (mental model). It

was also found that the average service time was independent of the customer arrival rate. That is, the increase in the subsystem service time was related to the mere presence of the control task and not to its level of difficulty. The subsystem event waiting time was also delayed by the simple presence of the control task. False alarm rate was much higher for the control task with the complex map than at the same task with the simpler map or no control task at all. Also there were more incorrect actions with no control task than with the control task with both simple and complex maps. These incorrect actions increased the average and standard deviation of waiting time for lower priority processes.

After investigating the adaptability of the queuing model of pilot decision-making in a flight management system, Walden and Rouse (1978) provided evidence that their queuing model permitted variations in the control task service rate so as to provide realistic predictions of the performance of the subsystem monitoring task. This successful application illustrates the potential use of this model in adaptive automation systems.

These mathematical models have proved useful in certain applications. However, they have some limitations. First, they require complicated computations even for simple tasks. Second, if implemented in an adaptive system, they require high expertise to calibrate, change, extend, and otherwise modify the software. Finally, these models are oriented toward abstracted parts of the task rather than the contextual reality within which these operations are actually achieved (Rouse et al, 1986).

There is also some concern whether modelling approaches such as intent inferencing or queuing theory are appropriate for a tactical environment. Most artificial intelligence (AI) approaches require production systems that are based on deductive logic and require a well-bounded problem. (AI approaches to decision making based on parallel distributed processing are still in their infancy.) Barrett & Donnell (1989) and Nau & Reggia (1986) argue that most human problem solving involves inductive or abductive reasoning. In particular, situation assessment may be an inductive process; and other real-world decision problems are too complex and too poorly bounded for current computational approaches (Barrett & Donnell, 1989). A tactical environment is difficult to predict because unforeseen tactics are not only possible, but likely. To put it more strongly, an adversary will do all it can (deception, new technology, etc) to create a non-stationary, unpredictable probabilistic environment. Barrett and Donell's (1989) argument is that in such highly non-linear situations human reasoning skills are more veridical than expert systems that depend upon deductive approaches.

This is not an argument against all modelling approaches. Barrett & Donnell (1989) proposed an architecture to combine human reasoning and machine computational abilities. Their approach to decision aiding utilizes the distinction between inductive and deductive reasoning as a basis for allocating functions

between the operator and machine components of a system.[7] Others have developed computational aiding systems based on abductive approaches wherein evidence implies a reduced subset of possible hypotheses (Nau & Reggia, 1986; Josephson et al., 1987). These modelling approaches are also congruent with the critical-event logic adaptive systems described above. A system driven by critical events leaves most of the situation assessment and high-level tactical reasoning to the human whereas the adaptive system performs in situations where either reaction time or complex computational requirements demand an automatic response.

Wickens' Multiple-Resource Theory. This theory grew out of considerations of the pattern of interference obtained in dual-task performance (Wickens, 1979, 1984). The theory postulates a limited set of information-processing structures or resources that jointly determine the degree to which performance interference occurs. That is, if two tasks compete for the same human information processing resource, and their combined resource requirements are much higher than the available resources, then interference will occur. The resources that Wickens (1984) considered included stages of processing (central processing versus response processing), modalities of input (visual/auditory) and output (manual/verbal), and type of coding in memory (verbal/spatial). The model has been very influential in engineering psychology and has stimulated a voluminous amount of research.

The multiple-resource model has several implications for time-sharing performance in a multitask environment (Wickens, 1984). First, if two (or more) tasks require the use of different resources (e.g., verbal/spatial codes) they will be time-shared efficiently. Second, if the two tasks share the same resources then there will be conflict in time-sharing the two operations and performance may suffer if the resource demand is high. Third, an increase in task difficulty will automatically cause an increase in the task demand in resources. And if some of these resources are needed for a concurrent task then the performance of the latter will be affected. In the case where those resources or part of them are not needed, then concurrent task performance will remain stable. Finally, if task difficulty is increased still further so that there is resource scarcity due to division between two tasks, then performance on each task will reflect the operators priorities.

The implications of this model for adaptive systems are fairly straightforward. This model helps allocate tasks that are not competing for the same resources. If competition takes place, the model will serve as a tool to assess the impact of that competition in order to appropriately allocate tasks to the computer and operator. The model offers information on how to solve the task allocation problem by distinguishing

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[7] This approach has been applied as a model in the Knowledgeable Operator Analysis- Linked System (KOALAS) for decision aiding and has in turn been applied to US Navy Command and Control (C^2) in an airborne electronic countermeasures system (AEW- RTAS) (Barrett, 1988; Stokes & Barrett, 1988a; Stokes & Barrett, 1988b).

between concurrent tasks and non-concurrent tasks. Evaluating the effect of competition between two tasks allows a better distinction of tasks between the pilot and the automation. In other words, the model allows the designer to decide when to automate a certain task or when to allow the human operator to carry out more than one task without affecting system performance adversely. Accordingly, a task is automated if its combination with a concurrent one would lead to a total demand on a specific resource that exceeds availability. Because the models predicts a distinction between a competitive task and a non-competitive task the system designer can design the adaptive logic to ensure that time-shared tasks do not compete for the same resources and hence degrade performance.

Central Executive Models. This type of model also analyses multitask performance by referring to information-processing structures and their associated resources. In contrast with Wickens' theory, however, this class of model assumes the existence of a central executive process which is modality free and supervises other subsystems under its control. Two such models will be discussed, Baddeley's (1986) working memory model, and Shallice's (1982) supervisory attention system model.

Baddeley (1986) developed his working memory model as a response to the "traditional" multi-store (e.g., short-term and long-term memory stores) models of memory. The theory, as originally articulated by Baddeley and Hitch (1974), argued that performance on a range of cognitive tasks required a "working memory", i.e. a temporarily active part of the memory system that was devoted to carrying out and storing partial computations required to execute a given cognitive task, such as reasoning or reading. In that sense working memory was not unique to so-called short-term memory tasks but was a general characteristic of many cognitive tasks.

On the basis of a review of existing memory research and his own studies, Baddeley (1986) postulated the need for a multicomponent working memory system. He proposed that working memory comprised a central executive that coordinated and directed the operation of two "slave" subsystems, the articulatory loop and the visuo-spatial "scratchpad". These two subsystems are respectively the working memory systems dealing with verbal and nonverbal processing respectively. In this respect, Baddeley's model is also a multiple-resource one like Wickens'. However, it differs from Wickens' model in postulating the need for a central, modality-free executive that oversees the operation of the two subsystems.

The articulatory loop subsystem is similar to a closed loop on a tape recorder. The loop contains a set of articulatory programs which are used to achieve the process of articulation, thus preventing the trace of the articulated stimulus from fading. The notion of stronger articulation leading to better recall fits nicely with this model. Moreover, findings about the impact of articulatory suppression also support the existence of this subsystem. The second postulated subsystem, the visuo-spatial scratchpad, deals with the

processing of visuo-spatial material. A general finding in the past has been that processing of sentences with large amounts of visual imagery are disrupted by visual processing, whereas, non-imageable or abstract phrases are disrupted by auditory processing. Baddeley and his colleagues found that the disruption of the operation of the scratchpad by a competitive tracking task affected long-term learning of manipulating visuo-spatial images. These results suggest the existence of a temporary visuo-spatial store which can retain and manipulate images and which is very sensitive to disruption by concurrent spatial processing. Finally, the central executive is considered modality free since it is supposed to relate between different subsystems which use specific modalities. Thus, the central executive has attentional capacities and the ability to select and operate control processes.

Shallice (1982) postulated a central executive model of human cognition that has similarities to Baddeley's model. He bases his executive control system on elementary units called schemas. Schemas are highly specialized routine programs that control a particular automatic (overlearned) action or skill such as opening a door or eating. These programs are *action* schemas, in that once triggered by a given appropriate stimulus, they "run off" processing operations automatically to lead to the desired and appropriate response. Shallice assumes that many schemas can be activated simultaneously at any given time because they are completely independent of each other. Most actions are controlled by schemata that are given the appropriate triggering. Schemata can operate at different levels from a simple conscious behavior to an overlearned one to a more complex form.

Thus far this model is not markedly different from other theories of automatic and controlled or effortful processing (Hasher & Zacks, 1979; Schneider & Shiffrin, 1977). The new feature is that the process of selecting the set of schemas to be run is postulated to involve two different processes (the distinction is qualitative): (1) *contention scheduling*, which is found in both automatic and controlled selection of action schemas, or in Shallice's words "routine and non routine selection"; and (2) the supervisory attentional system (SAS), which is involved only in controlled, effortful selection. In contention scheduling, selection is achieved according to priorities and environmental cues. Such a process is labeled "automatic conflict resolution" because it ensures the efficient use of different processing operations; thus avoiding probable conflict between different schemata (e.g., the use of the same response effector to two simultaneous inputs). The selection of a schema is ensured by mutual inhibition between different units. This inhibition needs to be maintained until the selected schema action is completed. Also schemas need to be maintained for extended periods of time so they can be used if appropriate environmental stimuli occur. In addition to this conflict resolution process, there is an overall controller: the SAS, which enables operations on schemas in every domain. In contrast to the contention scheduling mechanism, which is fast, routine, and inflexible, selection based on the SAS is slow, non routine, and flexible. The SAS biases the activation of schemata by favoring one schema over the others. It is a conscious attentional means of control. This selective

process is limited in capacity and is generally invoked in: (1) tasks that are involved in planning or decision making; (2) situations in which the automatic processes appear to be running into difficulties; (3) where novel or poorly learned sequences of acts are involved; or (4) where the situation is judged to be dangerous or technically difficult.

All of these conditions are likely to be ones in which automation may be invoked in the cockpit. The implications of this model for adaptive systems differ somewhat from those of the related resource models. As mentioned earlier, multiple resource theory (Wickens, 1979) predicts a deterioration in performance if two or more tasks compete for the same information processing resources. An adaptive system consistent with this model would invoke actions when the demands of competing tasks exceed the available resources. On the other hand, central executive models (Shallice, 1980; Baddeley, 1986) postulate that performance deterioration is not inevitable. If an operator needs to perform two concurrent actions, both of which are resource demanding, then the appropriate way to achieve it is to create a higher-order schema that oversee both sequences (Shallice, 1980). This may be possible through training or skill. In the case that both actions can be performed automatically without the need for the SAS, then they will be automatically synchronized and hence not need intervention from the adaptive system. Hence, resource demanding tasks (which require attentional control) must either be performed with synchrony or in alternation. Moreover, newly learned actions cannot be automatically performed because their schemas are small, relatively specialized sub-actions. Also, their triggering conditions are not compatible with the actual conditions that occur. In this case continual attentional monitoring is required and selection is delayed by deliberate attentional activation. On the other hand, well-learned actions are well defined and their schemas are relatively large, organized units of behavior. Their triggering conditions are very compatible to the current conditions. Once the schemas of well-learned actions have been selected, they can maintain control for long periods of time.

Based on the above mentioned points, the implications of this category of model for an intelligent aid can be defined as follows: 1) The model provides an assessment of the task sequences needing attentional control and those that do not need this type of control. Adaptation can thus be based on this requirement. 2) By determining when conditions permit or do not permit the activation of the supervisory attentional system, the model shows which tasks are easier to be carried out by the pilot or by the automaton. 3) The model can be used to assess when the human operator can carry out more than one task without harming overall performance. Thus, it could be used to decide the appropriate time to allocate certain tasks to the pilot or to the automation. This aspect of the model does not differ from other resource models, except that the predictions of task interference differ. 4) Shallice's model may be particularly well suited to test whether adaptive actions have adverse transient or long-term effects on performance. Such effects may take the form of a deterioration in performance following a transition from automated to manual mode, even though

resource models predict no degradation in performance. If the reversion to manual performance occurs after a very long period, the appropriate schema for multitask scheduling and coordination may need some time to be retrieved, "re-compiled" and activated. Thus performance may suffer. Alternatively, adaptive logic that rapidly cycles the pilot between automated and manual modes may also degrade performance because the appropriate schemata are not properly compiled in the first place. Research is currently ongoing to test these ideas. If support for such effects is found, the implication for adaptive algorithms will be that such adaptive methods will have to take into account time periods between cycles of automation and manual performance and adjust task allocation accordingly.

Training Issues

Successful training of pilots to use adaptive systems will be essential to the effectiveness of such systems. As discussed previously, automation can place conflicting demands upon pilots which they may not be well-equipped to meet (e.g. passive monitoring versus active control) unless they have been specifically trained to cope with these demands. However, training issues in automated systems have not received much attention, and in fact there is virtually no literature comparing different training methods for users of adaptive systems.

It was suggested earlier that inadequate training may lead to several automation-induced problems in the cockpit. For example, the negative effect of automation on monitoring performance may be related, in part, to a lack of "automation-based" skills. This reflects inappropriate training because automation necessitates a shift from psycho-motor skills to more cognitive and problem-solving skills, which may not be emphasized in the training program (Idaszak, 1989). Most training programs are based on eliciting appropriate responses from the pilot to display messages and flight conditions. Pilots are taught how to respond to a particular signal in a specific situation but, learning information-processing skills is not typically emphasized (Braune and Trollip, 1981).

Adaptive automation suggests the relevancy of adaptive training methods already in use. In contrast to adaptive automation research, there is a long history of research on adaptive training methods. It had long been held that adaptive training is a superior form of training, and many investigators advocated its feasibility. However, as Lintern and Gopher (1978) showed in a comprehensive literature review , the empirical evidence for its effectiveness was quite weak.

Adaptive training has generally been contrasted to more traditional part-task training. Adaptive training is the gradual increase in the difficulty and complexity of the training task. At first, a complex task

made up of several component tasks is made easy (by manipulating task component parameters) and presented at a slow rate, permitting the operator to quickly gain mastery. As efficiency increases, task difficulty and presentation speed are increased adaptively to keep performance levels roughly constant. On the other hand, part-task training is the presentation of different parts of the task individually. As mastery over the individual parts is gained, the whole task is gradually introduced. Research has focused on determining which of these training strategies is the more efficient.

It has been always argued that adaptive training has more advantages for learning over other methods and strategies. This claim is based on several assumptions: (1) learning any complex perceptual-motor skill has to be time-shared with its execution, which can interfere with learning (Klein & Posner, 1974); (2) decreasing the speed of presentation of the task components reduces achievement demands, which gives the subject more time to learn the task well (Gopher & North, 1977); and (3) the nature and the relationship of the task components when presented at a slow rate are the same as in the high-rate complex task.

In a study by Mane, Adams and Donchin (1989) the two training methods (adaptive and part training) were evaluated in a complex perceptual-motor task, referred to as "the Space Fortress". In the part training method, a subject was trained on important subtasks before he was presented with the whole task. In the adaptive strategy case, a subject was presented with the whole task where its time pressure was gradually corrected to the subject's performance until he reached a level where he could deal with the real-world task effectively. The results showed that part training was a more effective strategy than adaptive training. While compared to the control group (whole training), the part training group was clearly learning and performing better throughout the entire period of training. In the adaptive training situation, a negative transfer from slow to fast speed was found. This finding provides evidence that being trained in the slow speed mode, subjects found it difficult to adjust to the the high speed task. Such results confirm Lintern and Gopher's (1978) claim that adaptive training cannot be effective unless the transfer is substantial. That is, transfer has to be larger than the skills acquired by training during the difficult version (or fast speed in the present case). Another explanation for the present finding resides in the violation of the third assumption described earlier; since the relationship among the components of the task do not seem to be the same in the slow speed case as in the fast speed condition.

These results suggest that adaptive training methods alone may not be the most appropriate technique to help train users of automated systems, although they may still be helpful when combined with other methods. This is a somewhat unfortunate state of affairs, because the two concepts, adaptive automation and adaptive training, are related, and it would be parsimonious if a single unifying principle, could be applied both to the design of the automation and to the design of the training program for the users of automation for adapting to both his needs and abilities. Development of effective training techniques for

adaptive automation is a research priority because the shifting task requirements implicit in adaptive automation will require diagnostic and control skills substantially different from those of current, fixed automation aircraft. Unless these are developed, the anticipated benefits of adaptive systems may not be realized.

Preliminary Design Issues and Principles

Automation has traditionally been implemented using a technology-centered approach. In other words, as the technology has become available, automation has been introduced. The pitfalls of this design approach have been noted by many authors (Boehm-Davis et al., 1983; Normal et al., 1988; Wiener, 1988). In general, technology-centered design has had the effect of creating a cockpit environment that is not always fully compatible with the pilot's needs, capabilities, and limitations. Moreover, it has had the effect of removing the pilot from meaningful control of flight operations and relegating him to the "peripheral" role of a system monitor, at least in civilian automated aircraft. Numerous other examples of problems that this design philosophy can cause can be drawn, not just from the domain of aviation, but also from other areas such as process control and manufacturing.

The challenge for human factors professionals is to be able to propose viable design alternatives to technology-centered design. In other words, the time has come for going beyond simply pointing out the shortcomings of "traditional" approaches to automation (as indeed some of the previous sections of this paper have done!). What is required is a design philosophy that translates the "lessons learned" from past attempts at introducing automation into design guidelines for *automation that can be used effectively by the systems designer and human operator.* This will not be an easy task. However, a preliminary outline of such a *human-centered approach* to the design of adaptive automation can be sketched out here. The design issues and principles forming part of this approach must remain preliminary because of the paucity of empirical evidence concerning the effects of adaptive automation on pilot and system performance.

To begin, a human-centered approach to adaptive automation design should conform to the following general principles:

- The sophistication of the adaptive automation person-machine interface will make the use of a "systems approach" imperative. Particularly critical will be:
  - User control and information requirements are defined as completely as possible without regard to the capabilities of the technology.

- General function of the automated system(s) are identified early in the design effort: particularly with regard to the operator-machine interface.
- The technology of the automation system must be fully identified, along with its capabilities and constraints, before functional allocations are assigned to the operator or the automation system.
- Assumptions regarding the capabilities and function of the automation system must be explicitly defined in the course of the design effort. These assumptions will serve to drive all aspects of the system design effort, how operators utilize the system, and how the operators are trained to use the system.
- Mission design narratives and scenarios appropriate for use in the assessment of the complete operator-machine interface are developed and utilized throughout the design effort to validate and assess the design of the automation system.
- Functional analyses are performed for all aspects of the pilot decision-making process. Hierarchical functional flow diagrams are then generated to show the complete decision-making process.
- Identify functional requirements and perform function allocation to the operator and automation system given the operator's information and control requirements.
- Information and control requirements will need to be developed in an iterative fashion along with the development of the system function allocation throughout the system design process.

• The successful design of an adaptive automation system will depend on a clear and explicit statement of the system's design objectives. These objectives will have to address a variety of factors not typically found in the design of more traditional aircraft systems.

- A functional taxonomy (as opposed to task taxonomy) may prove necessary in determining what decisions in the automation system are best made by the pilot, and which are best made by the automated decision making system. In this way, a person-machine system incorporating adaptive automation will fully exploit the unique capabilities of *human intelligence* and not rely solely on machine intelligence (expert systems). Important capabilities include the ability to

recognize unusual configurations (cf. expert systems), learning from errors, adapting to partial information,etc. [8]

- The success of an adaptive automation system will probably depend on the explicit identification of the roles for the human operator(s) of the system and the automation system, as well as explicit rules of conduct as to how they should interact. Adherence to these rules and roles would allow the pilot to comprehend and anticipate the shifting of function allocations by the adaptive automation systems. In effect, through considering the system design from a person centered (psychological) perspective, the system will fulfill its stated operational goals, and would not violate its basic assumptions and objective. In essence, adaptive automation systems must incorporate a philosophy regarding the relationship of the pilot and the automation. This philosophy must be defined early in the design process and adhered to throughout.

- Automation systems must be designed to accommodate the needs of their users, and not the other way around, if the operators are going to actually use the system.

- The development of an adaptive automation system will necessitate the establishment of performance criteria in concert with the development of design objectives. These criteria will then be utilized throughout the system development process as a metric of the systems (prospects for) success. In this way, it may be ensured that the mission effectiveness resulting from using adaptive automation be equal to, or greater than, mission effectiveness without the adaptive automation.

• A probable design goal in the development of an adaptive automation system will be to optimize pilot workload, rather than simply minimize it.

[8]Exceptions to this rule are possible only in certain tactical situations (i.e. when an immediate life-and-death threat is involved and there is sufficient time for the system to get pilot acceptance). However, such exceptions should be restricted to such instances and hence should be relatively infrequent.

- In general, automation systems must be designed so that the pilot remains "in charge" of the automation and remains constantly aware of its activities. All efforts should be made to require the pilot's consent to any actions that the automation system undertakes.[9]

- The long-term impact of automation on pilot skills and performance must be considered early in the design process and considered throughout the system design process.

  - The impact of long-term experience on the development and/or decrement of pilot manual control and decision making skills, must be examined and understood in the context of the person-machine system's mission.

  - Effective training programs must be designed to optimize the pilot's contribution to mission effectiveness in the aircraft adaptive automation system.

Much conceptual analysis and empirical research is required before these general principles can be translated into emergent design principles that can be used by system designers. A more complete treatment of this area must therefore await the outcome of ongoing research in a number of laboratories that is aimed at investigating various aspects of the effects of adaptive automation on pilot and system performance. What is clear, however, is this research will serve primarily to fill in the details of answers to specific design questions. The framing of the high-level design questions can already be started (and some high-level answers provided), and we have presented some preliminary ones below. While further work is required to categorize these design questions into a coherent, unified framework, in general the framing of these design questions stems from a human-centered philosophy of automation.

Implementation of adaptive systems in advanced cockpits requires analysis of a number of design questions. The questions that are asked (and those that are not) implicitly define the design philosophy. Some preliminary questions that illustrate some of the issues and principles discussed in previous sections of this report are presented below. These are presented in a hierarchical manner, such that answers to top-level questions feed into lower-level questions. Component issues and potential solutions are given in more detail in Table 1.

- Should the automation be "static" or adaptive?

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9 While parallel distributed processing (i.e. "neural network") systems have some of these charactoristics, they have been primarily applied to pattern recognition problems and have yet to be shown to be capable of handling complex decision-making and problem solving.

- Who does the adapting?
- When is adaptation invoked?
- How is adaptation invoked?
- What measurement technology should be used?
- What logic should measurement-based adaptive systems use?
- What logic should modelling-based adaptive systems use?
- How is invocation of adaptation communicated to the pilot?
- Should "cycles" of automation be regulated in time?

The trends in aircraft design call for increasing complexity, therefore making the system management demands on the pilot-vehicle interface increasingly complex as well. Thus, the need for automation in the pilot-vehicle interface becomes a necessity. Automation holds the promise of reducing much of the pilot's task complexity, however, it also holds much of the responsibility for creating it. If automation is to fulfill its promise, it is important that we carefully study, and come to understand, how it impacts upon both the pilot and overall system performance. We, as system designers, must be careful not to exaggerate claims about automation until further empirical evidence is available. We have already seen that the benefits of existing cockpit automation has been tempered by real-world problems, and the concerns expressed by the users of these systems. We must constantly ask: Will automated systems actually increase workload? What happens to operator skill levels as we increase the levels of automation? How does the introduction of increasingly sophisticated automation change the nature of the tasks being performed by the systems' human operators?

It is inappropriate to incorporate new automation technologies into a system as complex as the modern, and future cockpit, until we have come to understand how this will impact all aspects of system operation. It is unrealistic to expect pilots to accept this technology and to utilize it to its full potential until they can understand it, its capabilities and limitations, and may be assured of its reliability and safety. To this end, as system designers and researchers, we must accept the responsibility for adapting an adaptive automation system to its end users. We must consider the individual needs of each user, and accommodate these needs through system design and training when necessary and possible.

The successful resolution of the problems and concerns represented by the application of adaptive automation technology, will require a multi-disciplinary approach. Specialists from such areas as human-computer interaction, interface design, and training, will be needed on the design team so that an integrated systems approach may be employed. We ask the reader to remember that the preliminary design issues and principles offered here, are prospective and evolutionary in nature. As additional information is gathered and refined, it is anticipated that potential solutions (and additional questions) will be raised and discussed in the context of the next generation combat aircraft.

TABLE 1

PRELIMINARY DESIGN ISSUES AND PRINCIPLES FOR ADAPTIVE AUTOMATION IN AVIATION SYSTEMS

1. **SHOULD AUTOMATION BE "STATIC" OR ADAPTIVE?**

    1.1 Static Automation
    1.2 Adaptive Automation √

2. **WHO DOES THE ADAPTING?**

    2.1 System Designer
    2.2 Pilot
    2.3 C^3I System
    2.4 Adaptive System √
    2.5 Adaptive System with Pilot Input √

3. **WHEN IS ADAPTATION INVOKED?**

    3.1 Off-line
        3.1.1 Mission Phase
        3.1.2 Pre-programmed Mission Phase
    3.4 On-line
        3.4.1 Critical Events (Programmed for Off-line)
        3.4.2 On-line (At times determined by Pilot Measurement or Modelling)√
    3.4 Combined Off-line/On-line √

4. **HOW IS ADAPTATION INVOKED?**

    4.1 Critical-Event Logic
    4.2 Pilot Measurement
        4.2.1 Static Workload Assessment
        4.2.2 Dynamic Workload Assessment √
        4.2.3 Psychophysiological Assessment
    4.3 Pilot Performance Modelling √
        4.3.1 Optimal Performance (Mathematical) Modelling
            4.3.1.1 Queuing Theory
            4.3.1.2 Sampling and Supervisory Control Theory
        4.3.2 Human Information Processing Modelling
            4.3.2.1 Multiple Resource Theory
            4.3.2.2 Central Executive Models
            4.3.2.3 Inference (Intention) Modelling.

5. **WHAT MEASUREMENT TECHNOLOGY SHOULD BE USED?**

    5.1 Primary-task
    5.2 Secondary-task
        5.2.1 Probe reaction time
        5.2.2 Sternberg task
        5.2.3 Random number generation

TABLE 1 Contd.

- 5.3 Psychophysiological
  - 5.3.1 ERPs (P300, N100)
  - 5.3.2 EEG
  - 5.3.3 Heart rate variability
- 5.4 Subjective
  - 5.4.1 NASA-TLX
  - 5.4.2 SWAT
  - 5.4.3 OWLKNEST
- 5.5 Combined
  - 5.5.1. WC FIELDE

6. WHAT ADAPTIVE LOGIC SHOULD MEASUREMENT-BASED ADAPTIVE SYSTEMS USE?

- 6.1 Simple Workload Threshold (Workload "RedLine")
- 6.2 Dynamic Workload Threshold (Recent Workload History)
- 6.3 Workload Profile
- 6.4 Psychophysiological Activity Profile

7. WHAT ADAPTIVE LOGIC SHOULD MODELLING-BASED ADAPTIVE SYSTEMS USE?

- 7.1 Optimal (Mathematical) Model Prediction of Performance Decrement
- 7.2 Script-Based Inference Prediction
- 7.3 Information-Processing Theory Prediction of Processing Overload/Underload

8. WHAT ACTIONS DOES THE ADAPTIVE SYSTEM INITIATE?

- 8.1 Task Allocation
  - 8.1.1 Full-task Automation/Manual Control
  - 8.1.2 Part-task Automation/Manual Control
- 8.2 Task Aiding
  - 8.2.1 Warning Messages
  - 8.2.2 Problem Restructuring
  - 8.2.3 Diagnostic Help

9. HOW IS INVOCATION OF ADAPTATION COMMUNICATED TO THE PILOT?

- 9.1 Explicit
  - 9.1.1 Message Display
  - 9.1.2 Change in Pilot-System Interface
- 8.2 Implicit
  - 9.2.1 Transparent to Pilot

10. SHOULD "CYCLES" OF ADAPTATION BE REGULATED?

- 10.1 Short-Cycle Regulation
- 10.2 Long-Cycle Regulation

√ Preliminary Design Recommendation

REFERENCES

Adler, P. (1986). New technologies, new skills. California Management Review, 29, 9-28.

Baddeley, A. (1986). Working memory. New York: Oxford University Press.

Baddeley, A., and Hitch, G. (1974). Working memory. In G. Bower (Ed), Recent advances in learning and motivation (Vol 8). New York: Academic Press.

Barnes, M. ,and Grossman, J. (1985). The intelligent assistant concept for electronic warfare systems. China Lake, CA. NWC December (NWC TP 5585).

Barrett, C., and Donnell, M. (1989). Real time advisory systems: considerations and imperatives. In Information and decision technologies. Greenwich, CT: Andrew Sage, Ed. Press.

Barrett,C.L. (1988) The Knowledgeable Operator Analysis-Linked Advisory System (KOALAS) Approach to Decision Support System Design. Analysis and Synthesis (Interim Report). Warminster, PA: Naval Air Development Center.

Beatty , J. (1986). The pupillary system. In M G H Coler, E Donchin & S. W .Porges (Eds). Psychophysiology: Systems, processes and applications. New York: Guilford Press.

Blumenthal, M., and Dray, J. (1985). The automated factory: Vision and reality. Technol. Rev, pp. 29-37.

Boehm-Davis, D., Curry, E. R., Wiener, E. L.,and Harrison, R. L. (1983). Human factors of flight-deck automation: Report on a NASA industry workshop. Ergonomics, 26, 953-961.

Carriero, N. (1977). Physiological correlates of performance in a long duration repetitive visual task. In R. R. Mackie (Ed), Vigilance: Theory, operational performance and physiological correlates (pp 307-330). New York: Plenum Press.

Chu, Y., and Rouse, W. (1979). Adaptive allocation of decision making responsibility between human and computer in multi-task situations. Proceedings of the IEEE and Cybernetics, SMC-7, 153-161.

Curry, R. E. (1979). Human factors of descent energy management. In Proceedings of the Institute of Electrical and Electronic Engineers Conference on Decision and Control, Ft Lauderal. December.

Curry, R. E. (1985). The introduction of new cockpit technology: A human factors study. NASA Technical Memorandum 86659.

Defense News (February,1989) Soviets gain in warheads, energy, and optics.

Donchin, E. (1980). Event-related potentials---Infering cognitive activity in operational settings. In Gomer F. E (Ed) Biocybernetic applications for military systems. McDonnell Douglas Technical Report MDC EB1911.

Donchin, E., Kramer, A. F., and Wickens, C. (1986). Applications of brain event-related potentials to problems in engineering psychology. In M. G . H Coles, E. Donchin & S. Porges (Eds), Psychophysiology: Systems, processes and applications (pp. 702-718). Middletown, N.J: Till & Till.

Edwards, E. (1977). Automation in civil transport aircraft. Applied Ergonomics, 84, 194-198.

Eggermeier,and O'Donnell. (1986). Workload assessment technology. In K. Boff, L. Kaufman, & J. Thomas (Eds.) Handbook of perception and human performance, Vol. 2, Cognitive processes and performance. New York: Wiley.

Fitts, P. (1961). Analysis of factors contributing to 460 "pilot error" experiences in operating aircraft controls. In Selected Papers on Human Factors in the Design and Use of Control Systems. Ed. W. Sinaiko, pp 332-58. New York. Dover.

Freedy, A., Madni, A., and Samet, M. (1985) Adaptive user models methodology and applications in man-computer systems. In W. B Rouse (Ed). Advances in man-machine systems research. Greenwich. CT. JAI Press.

Fuld, R. B., Liu, Y., and Wickens C. D. (1987). The impact of automation on error detection: Some results from a visual discrimination task. Proceedings of the Human Factors Society. 31st Annual Meeting 156-160.

Geddes, N. (1985). Intent inferencing using scripts and plans. Proceeding s of the First Annual Aerospace Applications of Artificial Intelligence Conference.

Gomer, F. E. (1980). Biocybernetic applications for military systems. McDonnell Douglas Technical Report MDC EB1911.

Gopher, D. , and North. (1977). The conditions of training in time-sharing performance. Human Factors, 19. 583-94.

Govindaraj, T., and Rouse, W. (1981). Modeling the human controller in environments that include continuous and discrete tasks. IEEE Transactions on Systems, Man and Cybernetics, SMC-11, 410-417.

Greenstein, J., and Revesman, M. (1986). Development and validation of mathematical model of human decision making for human-computer communication. IEEE Transaction on Systems, Man, and Cybernetics, 449-452.

Hancock, P. A. , and Chingnell, M. H. (1988). Mental workload dynamics in adaptive interface design. IEEE Transactions on Systems, Man and Cybernetics, 18, 647-658.

Hancock, P. A., Chignell, M. H., Vercruyssen, and Denhoff, M. (1989). Experimental evaluations of a model of mental workload. In Proceedings of the Human Factors Society 33rd Annual Meeting (pp. 1233-1237). Santa Monica: Human Factors Society.

Hancock, P. A., and Meshkati, N. (1988). Human mental workload. Amsterdam: Elsevier.

Hancock, P. A., Chignell, M. H., and Lowenthal, A. (1985). An adaptive human-machine system. Proceedings of the IEEE Conference on Systems, Man and Cybernetics, 15, 627-629.

Hasher, L., & Zacks, R. (1979). Automatic and effortful processes in memory. Journal of Experimental Psychology: General, 108, 356-388.

Hillyard, S. A., and Kutas, M. (1983). Electrophysiology of cognitive processing. Annual Review of Psychology

Hirschhorn, L. (1984). Beyond mechanization: Work and technology in a postindustrial age. Cambridge, MA: MIT Press.

Hoagland, M. (1984). The rage to automate. An interview with Captain Mel Hoagland by William L. Peterson. Air Line Pilot, 15-17.

Idaszak, J. R., and Hulin, C. L. (1989). Active participation in highly automated systems: Turning the wrong stuff into the right stuff. Technical Report, Aviation Research Laboratory. Institute of Aviation, University of Illinois at Urbana Champaign.

Johannsen, G., and Gavindaraj, T. (1980). Optimal control model predictions of system performance and attention allocation and their experimental validation in a display design study. Proceedings of the IEEE Conference on Systems, Man and Cybemetics. SMC-10, 249-261.

Jennings, J. R. (1986). Bodily changes during attending. In M .G. H. Coles, E. Donchin, and S .W .Porges (Eds). Psychophysiology: Systems, processes and applications. New York: Guilford Press.

Jordan, N. (1963). Allocation of functions between man and machines in automated systems. Journal of Applied Psychology, 47, 161-165.

Josephon, B., Chandraskaren, J., and Tanner, M. (1987). A mechanism for forming composite explanatory hypothesis. IEEE Trans Sys, Man & Cyber, SMC-17 , 445-458.

Kibbe, M. P., and Wilson, S. B. (1989). Information transfer from intelligent EW displays. Technical Report. Naval Weapons Center. China Lake CA 93555-6001.

Lintern, G., and Gopher, D. (1978). Adaptive training: issues, results and future directions. International Journal of Man-Machine Studies. 10, 521-51.

McDaniel (1988). Rules for fighter cockpit automation. Paper presented at the IEEE National Aerospace and Electronics Conference. New York: IEEE, 831-838.

Moray, N. (1984). Attention to dynamic visual displays in man-machine systems. In R. Parasuraman & R. Davies (Eds) The psychology of vigilance. Academic Press.

Moray, N. (1979). Mental workload: Its theory and measurement. New York: Plenum.

Morris, N. M., and Rouse, W. B. (1986). Adaptive aiding for human-computer control: Experimental studies of dynamic task allocation (Report No AAMRL-TR-86-005).

Morris, N. M., Rouse, W. B. ,and Ward S. L. (1984). Human-computer interaction: A conceptual model. IEEE International Conference on Systems, Man, and Cybernetics, Halifax, Nova Scotia, pp .178-183.

NADC. (1989). Adaptive function allocation for intelligent cockpits. Naval Air Development Center, Warminster, PA.

NASA . (1989). Proceedings of the Conference on Aviation Safety and Automation. Langley Research Center, VA: NASA.

National Research Council. (1982). Automation in combat aircraft. Committee on automation in combat aircraft, Air Force Studies Board, Washington, DC.

Nau, D. and Reggia, J. (1986). Relationship between deductive and abductive inferences in knowledge based diagnostic systems. In Expert Data Systems: First International Conference. Editor, L. Kreschberg.

Noah, W., and Halpin, S. M. (1986). Adaptive user interfaces for planning and decision aids in C3 I systems. IEEE Transactions on Systems, Man and Cybemetics. SMC 16, 909-918.

Noble, D. F. (1984). Forces of production: A social history of industrial automation. New York: Alfred A. Knopf.

Norman, S., Billings, C. E., Nadel, D., Palmer, E., Wiener, E. L., and Woods D. D. (1988). Aircraft automation philosophy: A source document. NASA, Ames Research Center. CA.

Norman, S. D., and Orlady, H. W. (1988). Flight-deck automation: Promises and realities. Proceedings of a NASA/FAA/industry Workshop organized by NASA Ames Research Center. Carmel Valley, CA. August 1-4.

Pallett, E. H. J. (1983). Automatic flight control, Edition 2. London: Granada Publishing Ltd.

Parasuraman, R. (1987). Human-computer monitoring. Human factors, 29, 695-706.

Parasuraman, R., and Bowers, J. C. (1987). Attention and vigilance in human-computer interactions. In Psychophysiology and the Electronic Workplace. A. Gale & B. Christie (Eds).

Parasuraman, R. (1990). Event-related brain potentials and human factors research. In Rohrbaugh, J. W, Parasuraman, R and Johnson, R. (Eds). Event-related potentials of the brain: Basic and applied findings. New York: Oxford University Press.

Reising,J. (1985). 2010: The symbionic cockpit. Proceedings of the IEEE National Aerospace and Electrical Conference. 1050-1054.

Riley , V. (1985). Monitoring the monitor: Some possible effects of embedding human models in highly automated manned systems. Proceedings of the IEEE Conference on Systems, Man and Cybernetics, 15, 6-9.

Rouse, W. B. (1977). Human-computer interaction in multitask situations. Proceedings of the 1977 IEEE Transactions in Systems, Man, and Cybernetics, SMC-7, 384-392.

Rouse, W. B. (1976). Adaptive allocation of decision making responsibility between supervisor and computer. In T. B. Sheridan and G. Johannsen (Eds), Monitoring behavior and supervisory control. New York: Plenum Press.

Rouse, W. B., and Morris, N. M. (1986). Understanding and enhancing user acceptance of computer technology. IEEE Transactions on Systems, Man, and Cybernetics, SMC-16. November/December.

Rouse, W. B. (1988). Adaptive aiding for human/computer control. Human Factors, 30(4), 431-443.

Rouse, W. B. , and Rouse, S. H. (1988). A framework for research on adaptive decision aids. Technical report. Air Force Aerospace Medical Research Lab. TR-83-082.

Rouse, W. B., and Rouse, S. H. (1983). A framework for research on adaptive decision aids. Air force Aeorospace Medical Research Laboratory. Ohio. AFAMRL-TR-83-082.

Rouse, W. B., Geddes, N. D., and Curry, R. E. (1986). An architecture for intelligent interfaces: Outline of an approach to supporting operators of complex systems. Human Computer Interaction, 3, 87-122.

Shiffrin, R. M., and Schneider, W. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending and a general theory. Psychological Review, 84, 127-190.

Shallice, T. (1982). Specific impairments of planning. Phil. Trans. Royal Society. London. B298, 199-209.

Sheridan, T., and Farrell, B. (1974). Man-machine systems. Cambridge: MIT Press.

Singleton, W . T. (1971). Psychological aspects of man-machine systems. In P. Warr (Ed). Psychology at work (pp 97-120) London. Penguin.

Stokes,J.M., and Barrett,C.L. (1988a). Incorporating AEW-RTAS in a KOALAS Environment: A concept demonstration of an Intelligent CICO Workstation. Analytics Technical Report 2100.11a. Warminster, PA: Naval Air Development Center.

Stokes, J.M., and Barrett, C.L.(1988b). The Modification of AEW RTAS: A KOALAS Concept Demonstration. Analytics Technical Report 2100.11b. Warminster, PA: Naval Air Development Center.

Walden, and Rouse, W. (1978). A queuing model of pilot decision making in a multi-task flight mangement situation. Proceedings of the 1978 IEEE Transactions on Systems, Man, and Cybernetics, SMC-8, 867-875.

Wickens, C. D. (1979). Measures of workload, stress and secondary tasks. In N. Moray (Ed.) Mental workload: Its theory and measurement (pp. 79-99). New York. Plenum.

Wickens, C. D. (1984). Processing resources in attention. In R. Parasuraman and D. R. Davies (Eds.) Varieties of attention. Orlando, FL: Academic Press.

Wickens, C. D. and Kessel, C. (1981). Failure detection in dynamic systems. In J. Rasmussen and W. B Rouse (Eds), Human detection and diagnosis of system failures. New York: Plenum.

Wickens, C. D., and Kramer, A. (1985). Engineering Psychology. Annual Review of Psychology.

Wiener, E. L. (1977). Controlled flight into terrain accidents: System-induced errors. Human Factors, 19, 171-181.

Wiener, E. L. (1985). Human factors of cockpit automation: A field study of flight crew transition. National Aeoronautics and Space Administration (NASA). Report 177333.

Wiener, E. L. (1988). Human factors in aviation. San Diego, CA. Academic Press.

Wiener, E. L. (1988). Cockpit automation. In E. L Wiener & D. C Nagel (Eds). Human factors in aviation. San Diego, CA. Academic Press.

Wiener, E. L., and Curry, R. E. (1980) Flight-deck automation: Promises and problems. Ergonomics, 23, (10), 995-1011.

Woods, D. D. (1988). Coping with complexity: The psychology of human behavior in complex systems. In L. P Goodstein, H. B. Andersen, and S. E. Olsen (Eds), Mental models, tasks and errors. London: Taylor & Francis.

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