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Team-Centered Perspective for Adaptive Automation Design

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Abstract

Automation represents a very active area of human factors research. The journal, Human Factors, published a special issue on automation in 1985. Since then, hundreds of scientific studies have been published examining the nature of automation and its interaction with human performance. However, despite a dramatic increase in research investigating human factors issues in aviation automation, there remain areas that need further exploration. This NASA Technical Memorandum describes a new area of automation design and research, called “adaptive automation.” It discusses the concepts and outlines the human factors issues associated with the new method of adaptive function allocation. The primary focus is on human-centered design, and specifically on ensuring that adaptive automation is from a team-centered perspective. The document shows that adaptive automation has many human factors issues common to traditional automation design. Much like the introduction of other new technologies and paradigm shifts, adaptive automation presents an opportunity to remediate current problems but poses new ones for human-automation interaction in aerospace operations. The review here is intended to communicate the philosophical perspective and direction of adaptive automation research conducted under the Aerospace Operations Systems (AOS), Physiological and Psychological Stressors and Factors (PPSF) project.

Introduction

> "During the 1970s and early 1980s...the concept of automating as much as possible was considered appropriate. The expected benefit was a reduction in pilot workload and increased safety...Although many of these benefits have been realized, serious questions have arisen and incidents/accidents that have occurred which question the underlying assumptions that a maximum available automation is ALWAYS appropriate or that we understand how to design automated systems so that they are fully compatible with the capabilities and limitations of the humans in the system."
>
> ---- ATA, 1989

The Air Transport Association of America (ATA) Flight Systems Integration Committee (1989) made the above statement in response to the proliferation of automation in aviation. They noted that technology improvements, such as the ground proximity warning system, have had dramatic benefits; others, such as the electronic library system, offer marginal benefits at best. Such observations have led many in the human factors community, most notably Charles Billings (1991; 1997) of NASA, to assert that automation should be approached from a "human-centered design" perspective.

The period from 1970 to the present was marked by an increase in the use of electronic display units (EDUs); a period that Billings (1997) calls "information" and "management automation." The increased use of altitude, heading, power, and navigation displays; alerting and warning systems, such as the traffic alert and collision avoidance system (TCAS) and ground proximity warning system (GPWS; E-GPWS; TAWS); flight management systems (FMS) and flight guidance (e.g., autopilots; autothrottles) have "been accompanied by certain costs, including an increased cognitive burden on pilots, new information requirements that have required additional training, and more complex, tightly coupled, less observable systems" (Billings, 1997). As a result, human factors research in aviation has focused on the effects of information and management automation. The issues of interest include over-reliance on automation, "clumsy" automation (e.g., Wiener, 1989), digital versus analog control, skill degradation, crew coordination, and data overload (e.g., Billings, 1997). Furthermore, research has also been directed toward situational awareness (mode & state awareness; Endsley, 1994; Woods & Sarter, 1991) associated with complexity, coupling, autonomy, and inadequate feedback. Finally, human factors research has introduced new automation concepts that will need to be integrated into the existing suite of aviation automation.

Clearly, the human factors issues of automation have significant implications for safety in aviation. However, what exactly do we mean by automation? The way we choose to define automation has considerable meaning for how we see the human role in modern aerospace systems. The next section considers the concept of automation, followed by an examination of human factors issues of human-automation interaction in aviation. Next, a potential remedy to the problems raised is described, called adaptive automation. Finally, the human-centered design philosophy is discussed and proposals are made for how the philosophy can be applied to this advanced form of automation. The perspective is considered in terms of the Physiological / Psychological Stressors & Factors project and directions for research on adaptive automation.

Automation in Modern Aviation

Definition. Automation refers to "...systems or methods in which many of the processes of production are automatically performed or controlled by autonomous machines or electronic devices" (Parsons, 1985). Automation is a tool, or resource, that the human operator can use to perform some task that would be difficult or impossible without machine aiding (Billings, 1997). Therefore, automation can be thought of as a process of substituting the activity of some device or machine for some human activity; or it can be thought of as a state of technological development (Parsons, 1985). However, some people (e.g., Woods, 1996) have questioned whether automation should be viewed as a substitution of one agent for another (see "apparent simplicity, real complexity" below). Nevertheless, the presence of automation has pervaded almost every aspect of modern lives. From the wheel to the modern jet aircraft, humans have sought to improve the quality of life. We have built machines and systems that not only make work easier, more efficient, and safe, but also give us more leisure time. The advent of automation has further enabled us to achieve this end. With automation, machines can now perform many of the activities that we once had to do. Our automobile transmission will shift gears for us. Our airplanes will fly themselves for us. All we have to do is turn the machine on and off. It has even been suggested that one day there may not be a need for us to do even that. However, the increase in "cognitive" accidents resulting from faulty human-automation interaction have led many in the human factors community to conclude that such a statement may be premature.

Automation Accidents. A number of aviation accidents and incidents have been directly attributed to automation. Examples of such in aviation mishaps include (from Billings, 1997):

DC-10 landing in control wheel steering
B-747 upset over Pacific
DC-10 overrun at JFK, New York
B-747 uncommanded roll, Nakina, Ont.
A320 accident at Mulhouse-Habsheim
A320 accident at Strasbourg
A300 accident at Nagoya
B-757 accident at Cali, Columbia
A330 accident at Toulouse
A320 accident at Bangalore
A320 landing at Hong Kong
B-737 wet runway overruns
A320 overrun at Warsaw
B-757 climbout at Manchester
A310 approach at Orly
DC-9 wind shear at Charlotte

Billings (1997) notes that each of these accidents has a different etiology, and that human factors investigation of causes show the matter to be complex. However, what is clear is that the percentage of accident causes has fundamentally shifted from machine-caused to human-caused (estimations of 60-80% due to human error) etiologies, and the shift is attributable to the change in types of automation that have evolved in aviation.

Types of Automation

There are a number of different types of automation and the descriptions of them vary considerably. Billings (1997) offers the following types of automation:

- **Open-Loop Mechanical or Electronic Control.** Automation is controlled by gravity or spring motors driving gears and cams that allow continous and repetitive motion. Positioning, forcing, and timing were dictated by the mechanism and environmental factors (e.g., wind). The automation of factories during the Industrial Revolution would represent this type of automation.

- **Classic Linear Feedback Control.** Automation is controlled as a function of differences between a reference setting of desired output and the actual output. Changes are made to system parameters to re-set the automation to conformance. An example of this type of automation would be flyball governor on the steam engine. What engineers call conventional proportional-integral-derivative (PID) control would also fit in this category of automation.

- **Optimal Control.** A computer-based model of controlled processes is driven by the same control inputs as that used to control the automated process. The model output is used to project future states and is thus used to determine the next control input. A "Kalman filtering" approach is used to estimate the system state to determine what the best control input should be.

- **Adaptive Control.** This type of automation actually represents a number of approaches to controlling automation, but usually stands for automation that changes dynamically in response to a change in state. Examples include the use of "crisp" and "fuzzy" controllers, neural networks, dynamic control, and many other nonlinear methods.

Levels of Automation

In addition to "types" of automation, we can also conceptualize different "levels" of automation control that the operator can have. A number of taxonomies have been put forth, but perhaps the best known is the one proposed by Tom Sheridan of Massachusetts Institute of Technology (MIT). Sheridan (1987) listed 10 levels of automation control:

1. The computer offers no assistance, the human must do it all
2. The computer offers a complete set of action alternatives
3. The computer narrows the selection down to a few
4. The computer suggests a selection, and
5. Executes that suggestion if the human approves, or
6. Allows the human a restricted time to veto before automatic execution, or
7. Executes automatically, then necessarily informs the human, or
8. Informs the human after execution only if he asks, or
9. Informs the human after execution if it, the computer, decides to

10. The computer decides everything and acts autonomously, ignoring the human

The list covers the automation gamut from fully manual to fully automatic. Although different researchers define adaptive automation differently across these levels, the consensus is that adaptive automation can represent anything from Level 3 to Level 9. However, what makes adaptive automation different is the philosophy of the approach taken to initiate adaptive function allocation and how such an approach may address the impact of current automation technology.

Impact of Automation Technology

Advantages of Automation. Wiener (1980; 1989) noted a number of advantages to automating human-machine systems. These include increased capacity and productivity, reduction of small errors, reduction of manual workload and mental fatigue, relief from routine operations, more precise handling of routine operations, economical use of machines, and decrease of performance variation due to individual differences. Wiener and Curry (1980) listed eight reasons for the increase in flight-deck automation: (a) Increase in available technology, such as FMS, Ground Proximity Warning System (GPWS), Traffic Alert and Collision Avoidance System (TCAS), etc.; (b) concern for safety; (c) economy, maintenance, and reliability; (d) workload reduction and two-pilot transport aircraft certification; (e) flight maneuvers and navigation precision; (f) display flexibility; (g) economy of cockpit space; and (h) special requirements for military missions.

Disadvantages of Automation. Automation also has a number of disadvantages that have been noted. Automation increases the burdens and complexities for those responsible for operating, troubleshooting, and managing systems. Woods (1996) stated that automation is "...a wrapped package -- a package that consists of many different dimensions bundled together as a hardware/software system. When new automated systems are introduced into a field of practice, change is precipitated along multiple dimensions." As Woods (1996) noted, some of these changes include: a) adds to or changes the task, such as device setup and initialization, configuration control, and operating sequences; (b) changes cognitive demands, such as requirements for increased situational awareness; (c) changes the roles of people in the system, often relegating people to supervisory controllers; (d) automation increases coupling and integration among parts of a system often resulting in data overload and "transparency"; and (e) the adverse impacts of automation is often not appreciated by those who advocate the technology. These changes can result in lower job satisfaction (automation seen as dehumanizing human roles), lowered vigilance, fault-intolerant systems, silent failures, an increase in cognitive workload, automation-induced failures, over-reliance, complacency, decreased trust, manual skill erosion, false alarms, and a decrease in mode awareness (Wiener, 1989).

Adaptive Automation

Disadvantages of automation have resulted in increased interest in advanced automation concepts. One of these concepts is automation that is dynamic or adaptive in nature (Hancock & Chignell, 1987; Morrison, Gluckman, & Deaton, 1991; Rouse, 1977; 1988). In an aviation context, adaptive automation control of tasks can be passed back and forth between the pilot and automated systems in response to the changing task demands of modern aircraft. Consequently, this allows for the restructuring of the task environment based upon (a) what is automated, (b) when it should be automated, and (c) how it is automated (Rouse, 1988; Scerbo, 1996). Rouse (1988) described criteria for adaptive aiding systems:

> The level of aiding, as well as the ways in which human and aid interact, should change as task demands vary. More specifically, the level of aiding should increase as task demands become such that human performance will unacceptably degrade without aiding. Further, the ways in which human and aid interact should become increasingly streamlined as task demands increase. Finally, it is quite likely that variations in level of aiding and modes of interaction will have to be initiated by the aid rather than by the human whose excess task demands have created a situation requiring aiding. The term adaptive aiding is used to denote aiding concepts that meet [these] requirements.

Adaptive aiding attempts to optimize the allocation of tasks by creating a mechanism for determining when tasks need to be automated (Morrison, Cohen, & Gluckman, 1993). In adaptive automation, the level or mode of automation can be modified in real time. Further, unlike traditional forms of automation, both the system and the pilot share control over changes in the state of automation (Scerbo, 1994; 1996). Parasuraman, Bahri, Deaton, Morrison, and Barnes (1992) have argued that adaptive automation represents the optimal coupling of the level of pilot workload to the level of automation in the tasks. Thus, adaptive automation invokes automation only when task demands exceed the pilot's capabilities. Otherwise, the pilot retains manual control of the system functions. Although concerns have been raised about the dangers of adaptive automation (Billings & Woods, 1994; Wiener, 1989), it promises to regulate workload, bolster situational awareness, enhance vigilance, maintain manual skill levels, increase task involvement, and generally improve pilot performance.

Strategies for Invoking Automation

Perhaps the most critical challenge facing system designers seeking to implement automation concerns how changes among modes or levels of automation will be accomplished (Parasuraman et al., 1992; Scerbo, 1996). Traditional forms of automation usually start with some task or functional analysis and attempt to fit the operational tasks necessary to the abilities of the human or the system. The approach often takes the form of a functional allocation analysis (e.g., Fitt's List) in which an attempt is made to determine whether the human or the system is better suited to do each task. However, many in the field have pointed out the problem with trying to equate the two in automated systems, as each have special characteristics that impede simple classification taxonomies. Such ideas as these have led some to suggest other ways of determining human-automation mixes. Although certainly not exhaustive, some of these ideas are presented below.

Dynamic Workload Assessment. One approach involves the dynamic assessment of measures that index the operators' state of mental engagement. (Parasuraman et al., 1992; Rouse, 1988). The question, however, is what the "trigger" should be for the allocation of functions between the pilot and the automation system. Numerous researchers have suggested that adaptive systems respond to variations in operator workload (Hancock & Chignell, 1987; 1988; Hancock, Chignell & Lowenthal, 1985; Humphrey & Kramer, 1994; Reising, 1985; Riley, 1985; Rouse, 1977), and that measures of workload be used to initiate changes in automation modes. Such measures include primary and secondary-task measures, subjective workload measures, and physiological measures. The question, however, is what adaptive mechanism should be used to determine operator mental workload (Scerbo, 1996).

Performance Measures. One criterion would be to monitor the performance of the operator (Hancock & Chignel, 1987). Some criteria for performance would be specified in the system parameters, and the degree to which the operator deviates from the criteria (i.e., errors), the system would invoke levels of adaptive automation. For example, Kaber, Prinzel, Clammann, & Wright (2002) used secondary task measures to invoke adaptive automation to help with information processing of air traffic controllers. As Scerbo (1996) noted, however,"...such an approach would be of limited utility because the system would be entirely reactive."

Psychophysiological Measures. Another criterion would be the cognitive and attentional state of the operator as measured by psychophysiological measures (Byrne & Parasuraman, 1996). An example of such an approach is that by Pope, Bogart, and Bartolome (1996) and Prinzel, Freeman, Scerbo, Mikulka, and Pope (2000) who used a closed-loop system to dynamically regulate the level of "engagement" that the subject had with a tracking task. The system indexes engagement on the basis of EEG brainwave patterns.

Human Performance Modeling. Another approach would be to model the performance of the operator. The approach would allow the system to develop a number of standards for operator performance that are derived from models of the operator. An example is Card, Moran, and Newell (1987) discussion of a "model human processor." They discussed aspects of the human processor that could be used to model various levels of human performance. Another example is Geddes (1985) and his colleagues (Rouse, Geddes, & Curry, 1987-1988) who provided a model to invoke automation based upon system information, the environment, and expected operator behaviors (Scerbo, 1996).

Mission Analysis. A final strategy would be to monitor the activities of the mission or task (Morrison & Gluckman, 1994). Although this method of adaptive automation may be the most accessible at the current state of technology, Bahri et al. (1992) stated that such monitoring systems lack sophistication and are not well integrated and coupled to monitor operator workload or performance (Scerbo, 1996). An example of a mission analysis approach to adaptive automation is Barnes and Grossman (1985) who developed a system that uses critical events to allocate among automation modes. In this system, the detection of critical events, such as emergency situations or high workload periods, invoked automation.

Adaptive Automation Human Factors Issues

A number of issues, however, have been raised by the use of adaptive automation, and many of these issues are the same as those raised almost 20 years ago by Curry and Wiener (1980). Therefore, these issues are applicable not only to advanced automation concepts, such as adaptive automation, but to traditional forms of automation already in place in complex systems (e.g., airplanes, trains, process control).

Although certainly one can make the case that adaptive automation is "dressed up" automation and therefore has many of the same problems, it is also important to note that the trend towards such forms of automation does have unique issues that accompany it. As Billings & Woods (1994) stated, "[i]n high-risk, dynamic environments...technology-centered automation has tended to decrease human involvement in system tasks, and has thus impaired human situation awareness; both are unwanted consequences of today's system designs, but both are dangerous in high-risk systems. [At its present state of development,] adaptive ("self-adapting") automation represents a potentially serious threat ... to the authority that the human pilot must have to fulfill his or her responsibility for flight safety."

The Need for Human Factors Research. Nevertheless, such concerns should not preclude us from researching the impact that such forms of advanced automation are sure to have on human performance. Consider Hancock's (1996; 1997) examination of the "teleology for technology." He suggests that automation shall continue to impact our lives requiring humans to co-evolve with the technology; Hancock called this "techneology."

What Peter Hancock attempts to communicate to the human factors community is that automation will continue to evolve whether or not human factors chooses to be part of it. As Wiener and Curry (1980) conclude: "The rapid pace of automation is outstripping one's ability to comprehend all the implications for crew performance. It is unrealistic to call for a halt to cockpit automation until the manifestations are completely understood. We do, however, call for those designing, analyzing, and installing automatic systems in the cockpit to do so carefully; to recognize the behavioral effects of automation; to avail themselves of present and future guidelines; and to be watchful for symptoms that might appear in training and operational settings." The concerns they raised are as valid today as they were 23 years ago. However, this should not be taken to mean that we should capitulate. Instead, because Wiener and Curry's observation suggests that it may be impossible to fully research any new technology before implementation, we need to form a taxonomy and research plan to maximize human factors input for concurrent engineering of adaptive automation.

Classification of Human Factors Issues. Kantowitz and Campbell (1996) identified some of the key human factors issues to be considered in the design of advanced automated systems. These include allocation of function, stimulus-response compatibility, and mental models. Scerbo (1996) further suggested the need for research on teams, communication, and training and practice in adaptive automated systems design. The impact of adaptive automation systems on monitoring behavior, situational awareness, skill degradation, and social dynamics also needs to be investigated. Generally however, Billings (1997) stated that the problems of automation share one or more of the following characteristics: Brittleness, opacity, literalism, clumsiness, monitoring requirement, and data overload. These characteristics should inform design guidelines for the development, analysis, and implementation of adaptive automation technologies. The characteristics are defined as:

- Brittleness refers to "...an attribute of a system that works well under normal or usual conditions but that does not have desired behavior at or close to some margin of its operating envelope."

- Opacity reflects the degree of understanding of how and why automation functions as it does. The term is closely associated with "mode awareness" (Sarter & Woods, 1994), "transparency"; or "virtuality" (Schneiderman, 1992).

- Literalism concern the "narrow-mindedness" of the automated system; that is, the flexibility of the system to respond to novel events.

- Clumsiness was coined by Wiener (1989) to refer to automation that reduced workload demands when the demands are already low (e.g., transit flight phase), but increases them when attention and resources are needed elsewhere (e.g., descent phase of flight). An example is when the co-pilot needs to re-program the FMS, to change the plane's descent path, at a time when the co-pilot should be scanning for other planes.

- Monitoring requirement refers to the behavioral and cognitive costs associated with increased "supervisory control" (Sheridan, 1987; 1991).

- Data overload points to the increase in information in modern automated contexts (Billings, 1997).

These characteristics of automation have relevance for defining the scope of human factors issues likely to plague adaptive automation design if significant attention is not directed toward ensuring human-centered design. The human factors research community has noted that these characteristics can lead to human factors issues of allocation of function (i.e., when and how should functions be allocated adaptively); stimulus-response compatibility and new error modes; how adaptive automation will affect mental models, situation models, and representational models; concerns about mode unawareness and situation awareness decay; manual skill decay and the “out-of-the-loop” performance problem; clumsy automation and task/workload management; and issues related to the design of automation. This last issue points to the significant concern in the human factors community of how to design adaptive automation so that it reflects what has been called “team-centered”; that is, successful adaptive automation will likely embody the concept of the “electronic team member”. However, past research (e.g., Pilots Associate Program) has shown that designing automation to reflect such a role has significantly different requirements than those arising in traditional automation design. The field is currently focused on answering the questions, “what is it that defines one as a team member?” and “how does that definition translate into designing automation to reflect that role?” Unfortunately, the literature also shows that the answer is not transparent and, therefore, adaptive automation must first tackle its own unique and difficult problems before it may be considered a viable prescription to current human-automation interaction problems. The next section describes the concept of the electronic team member and then discusses the literature with regard to team dynamics, coordination, communication, shared mental models, and the implications of these for adaptive automation design.

Adaptive Automation as Electronic Team Member

Layton, Smith, and McCoy (1994) stated that the design of automated systems should be from a team-centered approach; the design should allow for the coordination between machine agents and human practitioners. However, many researchers have noted that automated systems tend to fail as team players (Billings, 1991; Malin & Schreckenghost, 1992; Malin et al., 1991;

Sarter & Woods, 1994; Scerbo, 1994; 1996; Woods, 1996). The reason is what Woods (1996) calls "apparent simplicity, real complexity."

Apparent Simplicity, Real Complexity. Woods (1996) stated that conventional wisdom about automation makes technology change seem simple. Automation can be seen as simply changing the human agent for a machine agent. Automation further provides for more options and methods, frees up operator time to do other things, provides new computer graphics and interfaces, and reduces human error. However, the reality is that technology change has often resulted in the design of automated systems that are strong, silent, clumsy, and difficult to direct. Woods (1996) stated that these types of systems are "are not team players." The literature has described these as:

- Strong automation refers to automation that act autonomously and possess authority. A number of researchers (Billings, 1997; Norman, 1990; Sarter & Woods, 1994; Wiener, 1989) have noted that increased autonomy and authority creates new monitoring and coordination demands for operators of a system (Woods, 1996; Scerbo, 1996).

- Automation can also be silent; that is, the automation does not provide feedback about its activities. Sarter and Woods (1994) have noted that many operators often ask "what is it [the automation] doing?" This has been termed "mode awareness." Automation that is strong and silent lacks "transparency" (Billings, 1997) or "virtuality" (Mayher, 1992). The operator is not often aware what the system is doing and why; therefore, strong systems tend not "to communicate effectively" (Matlin & Schrenkenghost, 1992).

- Clumsy automation (Wiener, 1989) refers to automation that lightens crew workload when it is already low, but increases workload when situational demands become greater. As stated earlier, automation often requires human intervention to manage the automation at times when human attention should be focused elsewhere (e.g., scanning for traffic).

- Automation can also be difficult to direct when systems are designed to be intricate and laborious to manage.

A Team-Centered Approach. Billings (1997) argued for a "human-centered approach" that drives system design from the users' perspective. "Human-centered automation means automation designed to work cooperatively with human operators in pursuit of stated objectives." Although some (Sheridan, 1995) questioned the utility of the concept suggesting that it was an "oxymoron," Billings noted that humans are responsible for the outcomes of automation; therefore, humans should be the primary focus of any "team-centered" design. According to Billings, a human-centered design requires that the operator have authority and responsibility, that the operator must be always be informed, that operators must be able to monitor the automation, that the automation must be predictable, that the automation must also monitor the human, and that the two must communicate intent with each other. Billings suggested that these should serve as guidelines in the design of adaptive automation technology. Although human-centered automation is currently fashionable, its precise definition is difficult to pin down. It can mean:

- Allocating to the human the tasks best suited to the human and allocating to the automation the tasks best suited to it
- Maintaining the human operator as the final authority over the automation, or keeping the human in command
- Keeping the human operator in the decision and control loop
- Keeping the human operator involved in the system
- Keeping the human operator informed
- Making the human operator's job easier, more enjoyable, or more satisfying through automation
- Empowering or enhancing the human operation to the greatest extent possible through automation
- Generating trust in the automation by the human operator
- Giving the operator computer-based advice about everything he or she might want to know
- Engineering the automation to reduce human error and keep response variability to the minimum
- Casting the operator in the role of supervisor of subordinate automation control system(s)
- Achieving the best combination of human and automatic control, best being defined by explicit system objectives
- Making it easy to train operators to use automation effectively, minimizing training time and costs
- Creating similarity and commonality in various models and derivatives that may be operated by same person
- Allowing the human operator to monitor the automation
- Making the automated systems predictable
- Allowing the automated systems to monitor the human operator
- Designing each element of the system to have knowledge of the other's intent
- Ensuring automation has the characteristics of team players

Characteristics of Team Players. Malin and Schreckenghost (1992) discussed some of the characteristics of team players important for developing coupled, automated human-computer interaction. First, a team player is reliable; that is, a team member should reliably perform assigned tasks, which may require alternate ways of completing the assignment. Thus, intelligent systems should be designed to be both robust and flexible. A robust and flexible system would be able to perform when "things don't go as expected." Second, a team player communicates effectively with others. Intelligent systems must provide enough information so that the human understands what the computer is trying to do and why. However, the system must not provide so much information that the human becomes overloaded with it. Next, a team player must coordinate activities with others; that is team members must make sure that their performance does not interfere with others' performance. Furthermore, team members should be able to monitor each other and "back each other up." Therefore, intelligent systems must be designed so that both the computer and human are able to monitor each others' activities and exchange information about the tasks being performed. Finally, a team player is guided by a coach. The human, therefore, is both a team member who performs tasks, but also is a "coach" who manages and supervises the activities of the system. However, in some situations, the human may not be the "expert" and, therefore, the computer should be designed to provide advice (i.e., an expert system).

Factors Affecting Team Performance. In addition to characteristics of what makes a team player, it is also important for design of adaptive automation to consider those factors involved in optimal team performance. Nieva, Fleishman, and Rieck (1978) discussed four factors that have been shown to affect team performance. First, the knowledge, skills, and abilities (KSAs) are important contributions to successful team performance. The greater the KSAs, the greater the potential for team success. Next, task characteristics determine how individual and interdependent activities will impact the team cohesiveness. Third, team characteristics are important determinants of successful performance. Finally, the environment affects the ability of the team to accomplish directed objectives, such as winning games or completing stated tasks.

Fleishman and Zaccaro (1992) incorporated these four factors into a model of team behavior that emphasizes micro- and macro-level contributions to team behavior. They posited seven categories of team functions: motivation, systems monitoring, orientation, resource distribution, timing, response coordination, and procedure maintenance. These are defined as:

- Motivation concerns the stated team goals and other causal factors that engender team participation and cooperation.
- The systems monitoring functions refer to measurement issues regarding how team progress should be assessed.
- Orientation was defined as those factors that influence the acquisition and distribution of information, such as details about team goals, potential problems, delimiting factors, and so on.
- Resource distribution refers to the identification and allocation of tasks to individual members based upon their KSAs.
- Timing specifies the pace of work at both the individual and team levels.
- Response coordination identifies the sequence and timing of team member responses.
- Finally, procedure maintenance refers to the supervision of team behavior for compliance with stated and implicit organizational and societal norms and policies.

Scerbo (1994) compared these seven team functions to aviation automation. He suggested that there are a number of analogs for these functions to advanced automation concepts, such as adaptive automation (he specifically examined the taxonomy in the Pilot Associate (PA) and Adaptive Function Allocation for Intelligent Cockpits (AFAIC) program). Scerbo suggested that these characteristic programs illustrate the growing team-centered approach for automation design. However, he also noted that there are still many team-centered issues that remain to be explored in adaptive automation design (Scerbo, 1996). These team-centered issues include adaptive automation interface design and communication, supervisory control, and those involved in situation awareness maintenance and mental model development.

Adaptive Automation Interface. Scerbo (1996), in discussing the team-centered issues for adaptive automation, suggested that the design of adaptive automation should depend largely on the design of the interface. Effective communication among team members is critical for successful performance. However, Wiener (1993) stated that advanced automation has decreased crew coordination and resource management. Wiener (1989) cited some cockpit observations that identify several crew coordination issues:

- "Compared to traditional models, it is physically difficult for one pilot to see what the other is doing.... Though some carriers have a procedure that requires the captain (or pilot flying) to approve any changes entered into the CDU before they are executed, this is seldom done; often he or she is working on the CDU on another page [on the FMS] at the same time."

- "Automation tends to induce a breakdown of the traditional (and stated) roles and duties of the pilot-flying versus pilot-not-flying and a less clear demarcation of 'who does what' than in traditional cockpits. In aircraft in the past, the standardization of allocation of duties and functions has been one of the foundations of cockpit safety."

Therefore, in general, automated systems tend to decrease the communication among operators. Furthermore, automation may increase pilot error because the usual checks are impractical to implement (e.g., checking the accuracy of programming the FMS). In fact, Sears (1986) noted that 26% of aviation accidents were caused by inadequate cross check by the second crewmember. With adaptive automation, this figure has the potential to increase dramatically if human engineering doesn’t ensure sufficient transparent interface between flightcrew, ATC, and other aviation operators and adaptive automation.

The trend to design automation as an "electronic team member" conjures concern for crew cohesion and resource management. Wiener (1993) stated that the "glass cockpit" requires a great deal more interaction with the automation than with the other crewmembers. Often, the automation possesses the information to make decisions. However, as Scerbo (1996) said, "...humans use any and all available means to communicate with one another. Consider the wide range of options that individuals have available to them. They can use spoken and written language. They can draw diagrams and pictures. They may also use hand gestures, facial expressions, and eye contact." In addition, automated systems do not possess the richness of communication that humans do. Therefore, the design of adaptive automation systems must include as many mechanisms of communication as possible, such as text, graphics, voice, and video. This would allow operators to communicate more naturally with the automated system. As automation becomes more coupled and integrated, the need for designing "user-friendly" interfaces (see Williges, Williges, & Fainter, 1988) may ultimately decide the fate of adaptive automation. The increased advocacy of such automation concepts as "digital data link" further support the need to supply operators with pertinent information in a form that does not overload them with data. Also, Sarter and Woods (1993) noted that preferred interaction styles may affect the communication with the automation; for example, pilots may be resistant to the implementation of intelligent agents (i.e., adaptive automation) in the cockpit (see Potter & Foushee, 1988).

Supervisory Control and Adaptive Automation. "Automation of a task for long periods of time increases the demand on the operator to monitor the performance of the automation, given that the operator is expected to intervene appropriately if the automation fails. Because human monitoring can be subject to error in certain situations, understanding how automation impacts on monitoring is of considerable importance" (Parasuraman, 1996). Parasuraman (1994; 1996) also noted that monitoring performance is affected by automation reliability, automation consistency, cognitive and physical workload, and display factors. These factors affect operator characteristics such as complacency, trust, and over-reliance on automation ("use, disuse, misuse, and abuse" of automation; Riley & Parasuraman, 1997). Molloy & Parasuraman (1994) suggested that display integration and adaptive task allocation may serve as effective countermeasures. However, increased advance automation technology may require more prescriptive approaches.

The concern can be seen in Parasuraman's (1996) caution that "...human factors professionals will be severely challenged to come up with effective methods to help those who will be required to 'watch the computers'." For example, the increase in display integrality may actually lead to a "key-hole effect" (Billings, 1997) due to the great deal of information presented on a CDU. The key-hole effect is likened to reading a newspaper by only looking at one letter at a time (as though you place another piece of paper with a small aperture over the newspaper). You can decipher the information, but you miss the holistic perspective. Likewise, the design of integrated displays may increase the cognitive burdens of the operator. Furthermore, the opacity and brittleness (Billings, 1997) may decrease the accuracy of the mental model of the operator. Other important considerations for adaptive automation include risk and perceived risk, state learning, fatigue, operator confidence, KSAs, workload and perceived workload, trust, and system reliability (Riley, 1996). These human factors concerns associated with traditional automation can be significantly more deleterious for cockpits and ATC stations under adaptive automation. Because adaptive automation has the potential to dynamically change function allocation, making sure to keep the pilots and controllers "in-the-loop" becomes even more tantamount with such forms of automation.

Adaptive Automation and Situational Awareness. The problems of "key-hole" effect and "automation surprises" (Rudisill, 1994; Woods, 1997) and other issues cited as concerns of supervisory control are closely related to the concerns involved with situation awareness maintenance. Loss of situational awareness has been cited in the literature as an "out-of-the-loop" performance problem of potential for adaptive automation (Endsley, 1996). Wickens (1992) defines situational awareness as "the ability to rapidly bring to consciousness those characteristics that evolve during flight." The kinds of knowledge that "evolve" during flight include navigation awareness, systems awareness, task awareness, and temporal awareness. Endsley (1996) defined situational awareness as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future." She listed three levels of situational awareness: Situational awareness involves the process of detecting critical events in the environment (level 1 SA), comprehending the meanings of the event and relating the event to the person's goals (level 2 SA), and projecting the future state of the system (level 3 SA).

Operators who do not have situational awareness have been shown to be much slower at detecting and responding to automation failures (Ephrath & Young, 1981; Kessel & Wickens, 1982; Wickens & Kessel, 1979; Young, 1969). Billings (1991) argued that many aircraft accidents in which monitoring automation errors have occurred resulted mostly when (a) devices behaved reasonably, but incorrectly and (b) pilots were not alert to the state of automation. Furthermore, human operators often place too much trust in automated systems; a phenomenon termed "complacency." (Danaher, 1980; Parasuraman et al., 1994; Riley, 1994). This often leads to an over-reliance on automation further reducing situational awareness. Data from the Aviation Safety Reporting System (ASRS) on "near-accidents" shows how serious loss of situational awareness can be. In this database, pilots have reported that most of their mistakes are due to boredom and inattention. Pope and Bogart (1992) referred to this as a "hazardous state of awareness" because pilots are not attentive enough to react quickly to emergency situations. Therefore, human factors may contribute considerably to developing countermeasures in adaptive automation contexts.

Another cause for a loss of situational awareness involves the design of automated systems that fail to provide feedback to system operators. As Norman (1989) stated, "without appropriate feedback people are indeed out-of-the-loop. They may not know if their requests have been received, if the actions are being performed properly, or if problems are occurring." Automated systems often do not provide enough information or are opaque (lack information salience; Endsley, 1996). For example, some autofeathering systems often do not inform pilots that the system is shutting down an engine because of a malfunction. Another example is the FMS that provides multiple modes of automation organized as a hierarchical display (Billings, 1991; 1997). The opaqueness of many automated systems can hinder operators from developing an accurate mental model of the system (Norman calls this the "conceptual model"). This may also contribute to "mode errors" (Sarter & Woods, 1994) arising from an inability to decipher the intent of the automation and inappropriate mental model development of the automated system. Rudisill's (1994) article, Flight Crew Experience with Automation Technologies on Commercial Transport Flight Decks, illustrates the difficulty that operators experience in dealing with such systems. She reported that many pilots often ask such queries as, "what's it doing now?", "I wonder why its doing that?", and so on. Adaptive automation may only increase such queries and significantly degrade the safety of operations with such systems.

PPSF Project Perspective

The Physiological and Psychological Stressors and Factors (PPSF) project, under Aerospace Operations Systems (AOS), is concerned about the issues associated with adaptive automation that may increased, rather than mitigate, the “out-of-the-loop” performance problem. Research has shown that adaptive automation can significantly improve and enhance pilot performance, situation awareness, decision-making, and mental workload (e.g., Freeman, Mikulka, Prinzel, & Scerbo, 1999; Inagaki, 2000; Inagaki, Takae, & Moray, 1999; Parasuraman, Mouloua, & Molloy, 1996; Prinzel, Scerbo, Scerbo, & Mikulka, 2000; Scott, 1999). However, researchers have also reported increased return-to-manual deficits and automation surprises with adaptive automation (e.g., Prinzel, Hadley, Freeman, & Mikulka, 1999; Scallen, Hancock, & Duley, 1995). The PPSF project emphasizes that adaptive automation should only be initiated when doing otherwise would jeopardize safety (e.g., prototype F-16D Automatic Ground

Collision Avoidance System). Otherwise, adaptive aiding (Morrison & Gluckman, 1994; Parasuraman et al., 1992; Rouse, 1988) and training techniques should be used in conjunction with adaptive automation to help minimize the onset of hazardous states of awareness (FAA, 1996; Pope & Bogart, 1992). The PPSF project has been focused on a program of research to develop CRM^2 (i.e., CRM-squared) approaches to reduce the occurrence of these states of awareness in aviation.

The CRM^2 approach involves a combination of traditional Crew Resource Management (CRM) approach and a new Cognitive Resource Management (CRM) (i.e, CRM X CRM = CRM^2) approach. These two approaches use both inter-personal (i.e., Crew RM) and intra-personal (i.e., Cognitive RM) to reduce hazardous states of awareness. The methods of Crew Resource Management are well known and documented (e.g., Wiener, 1998) and focuses on how to improve team coordination and dynamics between flightcrews, ATC, flight attendants, etc. Because the success of adaptive automation may rest on the ability to design this form of automation from a "team-centered" perspective, Crew Resource Management concepts are important considerations for design. However, Rigner and Dekker (2000) stated that current pilot training (e.g., Multi-Crew Cooperation and CRM) is inadequate to develop the new attentional and knowledge requirements necessary to support pilot-automation interaction with new automated systems, such as adaptive automation.

Simmons (1998), a retired Vice President of Safety for United and NASA safety consultant, noted that, "…specific intrapersonal training should be developed and presented to all pilots to increase awareness of human error and the counteracting strategies that can reduce human error." He suggested that training should include training to understand and recognize hazardous thought patterns and hazardous states of awareness and also how best to self-regulate these states as part of any CRM training program --- this is what the PPSF project terms "cognitive resource management." The introduction of advanced automation, such as adaptive automation, would only increase the need for this form of training.

The PPSF project has been active in research on adaptive automation and developing CRM^2 training approaches to supplement advanced automation design. Prinzel, Pope, and Freeman (2002) represent an example of research conducted under the PPSF project. These researchers investigated cognitive resource management as a potential adjunct to adaptive automation design to reduce the potential of human factors problems of return-to-manual deficits and automation surprises. Prinzel, Pope, and Freeman reported that cognitive resource management training significantly improved the potential of adaptive automation and increased situation awareness, pilot performance, and lowered workload compared to those pilots not receiving any CRM training. Therefore, they concluded that CRM^2 could significantly enhance the skills of pilots and complement the benefits of adaptive automation.

Conclusion

The review of adaptive automation discussed the concept of adaptive automation and the human factors issues associated with design. Like the introduction of other new technologies, adaptive automation presents the opportunity to solve some problems, but may also introduce new ones. Adaptive automation is a new way of thinking about automation and, therefore, may require a new way of thinking about design. It is asserted that adaptive automation design needs to be from a "team-centered" design perspective. This NASA Technical Memorandum presented the philosophy of such an approach and provided project research issues with regard to it and adaptive automation design. Although the literature is replete with thoughts on how to do so, unfortunately, little empirical data exists to guide system designers seeking to implement this advanced form of automation. This was a similar conclusion reached by Hammer and Small (1995), commenting on the Pilot Associates program, who stated that "an examination of how humans decide to share tasks and information may be a more fruitful area in which to develop a theory of human-associate interaction." In practice then, it may be that consideration of adaptive automation based on what we know about human teams may be myopic for how to design electronic team members. Indeed, some research was presented that suggests that adaptive automation may require an entirely new way of thinking about automation "team-centered" design.

> At present, adaptive automation is still in its conceptual stages. Although prototypes do exist, it will take many years for the technology to mature. Fortunately, this gives designers, cognitive engineers, and psychologists a chance to begin studying the many issues that surround adaptive automation before implementation of the technology is widespread. We have a real opportunity at this point in time to guide the development of adaptive automation from an understanding of human requirements instead of from restrictions imposed by current technological platforms.
>
> ---- Scerbo, 1996

Adaptive automation is the next step in automation evolution but a big step it is, and it will require an equally big step in how we think about ourselves and how we are to relate to automation in the future. Because adaptive automation is likely to have a profound impact on how operators in aviation do their jobs, we must be careful not to constrain our thinking about how we are to do so. A "team-centered", or "social-centered" (Scerbo, 1996) way of thinking may likely provide the needed approach to ensure that adaptive automation is a prescription to, not contributor of, human factors shortcoming in human-automation interaction. However, we must be careful not to just transplant the area of research on human teams and blindly apply it to adaptive automation as though automation is to embody another person. Instead, we must seek to understand what is special about automation and how we can design adaptive automation so that it is indeed accepted as an "electronic team member." Furthermore, we must consider adaptive automation in the context of a multidimensional human factors solution to automation design and be willing to try new ideas about how we treat problems that affect human operators.

> "In broad terms, our mandate is to pioneer the future . . . to push the envelope . . . to do what has never been done before. An amazing charter indeed . . . NASA is what Americans . . . and the people of the world . . . think of when the conversation turns to the future.
>
> Sean O'Keefe
> NASA Administrator

The NASA mission is to conduct research that pushes the envelope in areas that have the potential to revolutionize our world. The PPSF project reflects that commitment through the endeavor of “team-centered” adaptive automation design. Moreover, the project objective is to break down barriers of “current technological platforms” and thinking about new, multidimensional solutions to problems of human-automation interaction. As Abraham Lincoln once advised, “distain the beaten path and seek regions hitherto unexplored.” NASA has internalized that vision as its very own --- “NASA is about creating the future” (O’Keefe, April 12, 2002). Yes, the barriers to adaptive automation design and potential risks are great, but the promises of adaptive automation are even greater. The PPSF project seeks to capitalize on these promises and help “create the future” through the support of research on this new but exciting direction in automation design and do so “as only NASA can” (NASA, 1999).

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13. ABSTRACT *(Maximum 200 words)*

Automation represents a very active area of human factors research. The journal, Human Factors, published a special issue on automation in 1985. Since then, hundreds of scientific studies have been published examining the nature of automation and its interaction with human performance. However, despite a dramatic increase in research investigating human factors issues in aviation automation, there remain areas that need further exploration. This NASA Technical Memorandum describes a new area of automation design and research, called "adaptive automation." It discusses the concepts and outlines the human factors issues associated with the new method of adaptive function allocation. The primary focus is on human-centered design, and specifically on ensuring that adaptive automation is from a team-centered perspective. The document shows that adaptive automation has many human factors issues common to traditional automation design. Much like the introduction of other new technologies and paradigm shifts, adaptive automation presents an opportunity to remediate current problems but poses new ones for human-automation interaction in aerospace operations. The review here is intended to communicate the philosophical perspective and direction of adaptive automation research conducted under the Aerospace Operations Systems (AOS), Physiological and Psychological Stressors and Factors (PPSF) project.

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