

On the Design of Adaptive Automation for Complex Systems

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ABSTRACT

This article presents a constrained review of human factors issues relevant to adaptive automation (AA), including designing complex system interfaces to support AA, facilitating human–computer interaction and crew interactions in adaptive system operations, and considering workload associated with AA management in the design of human roles in adaptive systems. Unfortunately, these issues have received limited attention in earlier reviews of AA. This work is aimed at supporting a general theory of human-centered automation advocating humans as active information processors in complex system control loops to support situation awareness and effective performance. The review demonstrates the need for research into user-centered design of dynamic displays in adaptive systems. It also points to the need for discretion in designing transparent interfaces to facilitate human awareness of modes of automated systems. Finally, the review identifies the need to consider critical human–human interactions in designing adaptive systems. This work describes important branches of a developing framework of AA research and contributes to the general theory of human-centered automation.

1. INTRODUCTION

Adaptive automation (AA) has been described as a form of automation that allows for dynamic changes in control function allocations between a machine and human operator based on states of the collective human–machine system (Hilburn, Byrne, & Parasuraman, 1997; Kaber & Riley, 1999). Interest in dynamic function allocation (DFA, or flexible automation)

has increased within the recent past as a result of hypothesized benefits associated with the implementation of AA over traditional technology-centered automation. Purported benefits include alleviating operator out-of-the-loop performance problems and associated issues, including loss of situation awareness (SA) and high mental workload. Though the expected benefits of AA are encouraging, there are many unresolved issues regarding its use. For example, there is currently a lack of common understanding of how human-machine system interfaces should be designed to effectively support implementation of AA.

In this article, current AA literature is reviewed in the context of a theoretical framework of human-centered automation research with the objective of identifying critical factors for achieving human-automation integration to support the effective application of AA to complex systems. We describe branches of a research framework supporting human-centered automation that seems to have been neglected by previous literature reviews, including the implications of the design of AA on operator workload and the effects of AA on human-computer interaction (HCI) and crew interaction. This work is important because an optimal approach to AA remains elusive. Developing a unified perspective of the aforementioned issues may serve as a basis for additional design guidance to structure AA applications beyond that previously provided.

1.1. Human-Centered Automation Theory and AA

A theory of human-centered automation closely related to AA states that complex systems should be designed to support operator achievement of SA through meaningful involvement of operators in control operations (Endsley, 1995b, 1996; Kaber & Endsley, 1997). Involvement may occur through intermediate levels of automation (LOAs) or through AA. Both techniques may be effective for increasing operator involvement in control operations as compared to full automation. Human-centered automation is concerned with SA because it has been found to be critical in terms of successful human operator performance in complex and dynamic system operations (cf. Endsley, 1995a). AA has been proposed as a vehicle for moderating operator workload or maintaining it within predetermined acceptable limits, based on task or work environment characteristics, to facilitate and preserve good SA (Hilburn et al., 1997; Kaber & Riley, 1999). Therefore AA might be considered a form of human-centered automation. Unfortunately, the relation between SA and workload presents a conundrum to those designing automation. Optimization of both SA and workload in the face of automation can prove difficult. Under low workload conditions associated with high levels of system automation, operators may experience boredom and fatigue due to lack of cognitive involvement, or interest in, control tasks. Operators of autonomous systems are often forced into the task of passive monitoring of computer actions rather than active task processing. Even when attending to the monitoring task, decreased task involvement can compromise operator SA (Endsley & Kaber, 1999; Endsley & Kiris, 1995; Pope, Comstock, Bartolome, Bogart, & Burdette, 1994). This is an important issue because operators with poor SA may find it difficult to reorient themselves to system functioning in times of system failure or unpredicted events. Therefore, automated system performance under failure modes may be compromised.

Conversely, cognitive overload may occur when operators must perform complex, or a large number of, tasks under low levels of system automation (e.g., complete manual control). High workload can lead directly to low levels of SA and task performance, as opera-

tors struggle to keep up with the dynamically changing system. Increasing task requirements beyond that which the human is cognitively capable of managing can also lead to feelings of frustration and defeat, as well as a loss of confidence in ability to complete the task. The operator may then become detached from the task, resulting in loss of SA. Again, the loss of SA can lead directly to poor human–machine system performance.

The first situation described above may be due to system and task design. The second situation may result from operator reactions to a difficult task. It should be noted that, between these two extremes, it has been found that SA and workload can vary independently (Endsley, 1993). The challenge for AA research is to identify the optimal workload, or functional range, under which good levels of operator SA and total system performance will be possible.

The key issues that must be addressed to meet this need include determining how the design of automation or AA methods affect operator workload and how system information should be communicated to operators to facilitate SA under AA. Several studies have demonstrated positive results in terms of operator SA when applying AA as an approach to human-centered automation of complex systems. For example, Kaber (1997) observed improvements in SA in a simulated automatic dynamic, control task (“radar” monitoring and target elimination) when using a preprogrammed schedule of periodic shifts of task control between intermediate- and high-level automation and manual control, as compared to fully autonomous or completely manual control. Although important for establishing preliminary system design guidelines and providing insights into methods of AA, this work and other recent studies (e.g., Kaber & Riley, 1999) have been conducted using specific task and operational scenarios and, therefore, results may have limited generalizability to a broad range of systems.

Unfortunately, at this point there exists no theory of AA that can optimally address SA and workload tradeoffs across all types of complex systems (e.g., air traffic control, production control, and telerobotic systems). This article seeks to address this issue by supporting the concept of human-centered automation and presenting an understanding of aspects of the relation of AA to SA and workload not previously explored in detail.

1.2. Previous Research

Preliminary or casual reviews of AA research have been published (cf. Parasuraman, Mouloua, Molloy, & Hilburn, 1996; Scerbo, 1996), summarizing empirical studies of the concept, which make inferences toward a general theory of AA. For example, Scerbo’s work includes a brief review of traditional automation, proposed AA mechanisms and strategies, and potential benefits and concerns with the implementation of AA. Our work complements this effort by discussing some new issues, such as

1. Failures in AA design to consider operator workload requirements associated with managing dynamic control allocations between themselves and automated systems in addition to maintaining system task responsibilities.
2. The need to determine how human–computer interfaces should be designed to support effective human–automation communication under AA.
3. The need to evaluate the impact of implementation of AA on human crew interactions in systems control.

These issues are considered in the context of the human-centered automation theory with the intent of developing a more complete knowledge of AA.

2. WORKLOAD AND AA

Unfortunately, it has been observed through empirical study of AA that operators of many complex, dynamic systems may experience workloads above desired levels as a result of concentrating on control function allocations and maintaining task responsibilities simultaneously (Kaber & Riley, 1999; Scerbo, 1996). An increase in human operator workload associated with introduction of automation in complex systems is not a new issue. Selcon (1990) observed that fighter aircraft pilot perceptions of flight workload increased significantly with the introduction of automated decision aids into aircraft cockpits.

There are two general cases in which perceived workload increases may occur in applications of AA. First, operators may perceive increased cognitive load in monitoring computer management of function allocations between themselves and automated subsystems (Endsley, 1996). This may be due in part to operator anxiety about the timing of allocations and the need to complete a particular task during system operations. It may also be attributed to an additional load on the visual channel in perceiving task-relevant information on “who is doing what.”

The second involves implementation strategies of AA where the human has the task of managing function allocations in addition to performing routine operations. Under these circumstances, workload increases may be even greater than that associated with monitoring computer-based dynamic control allocations (Selcon, 1990). Additional problems indicate operators may have trouble in identifying when they need to switch from manual to automated modes or vice versa (Air Transport Association, 1999). Failures to invoke automation or manual control have been identified as occurring due to operator overload, incapacitence, being unaware of the need for a different LOA, or poor decision making (Endsley, 1996).

Kaber and Riley (1999) studied the effect of AA on operator workload during dual-task performance involving a primary dynamic control task and an embedded secondary monitoring task. Participants in this study were provided with a computer decision aid that either suggested or mandated DFAs between manual and automated control of the primary task based on participant performance in the secondary task. The authors' objective was to maintain secondary task performance within 20% of optimal performance observed during testing in the absence of primary task control. Average secondary task performance levels during dual-task functioning were within approximately 30% of optimal secondary task performance. It is important to note that when the primary task was fully automated, secondary task performance was within 5% of optimal. However, automated primary task performance may not have been superior to AA of the task. Kaber and Riley attributed the observed decrease in performance (indicative of increased workload) to the need for individuals to monitor automated dynamic control allocations or to manage them, which was not considered in establishing optimum secondary task performance baselines or the design of the dual-task paradigm. This is an important issue that needs to be considered by future research to ensure that AA achieves the objectives of human-centered automation (i.e., moderating workload and maintaining SA). Methods

for dealing with AA-induced workload must be devised. A critical step to developing such techniques would be to evaluate operator workload associated with the implementation of general AA strategies separate from system task workload. These workload components could then be used to drive AA design.

3. INTERFACE DESIGN FOR AA

In addition to considering the effects of AA on workload, the effects on operator SA must also be considered. Implementation of AA may introduce added complexity into system functioning and control. Consequently, operators require advanced interfaces that are useful for dealing with this complexity to enhance, rather than hinder, system performance. AA will require extra attention to developing interfaces that support operator SA needs at varying LOAs and in ways that support their ability to transition between manual and automated control and back again.

Scerbo (1996) suggested that the success of AA will in large part be determined by system interface designs that include all methods of information exchange (e.g., visual, auditory, haptic, etc.). With this in mind, one goal of the interface design for AA systems is akin to that of HCI research, that is, to facilitate the transmission of information to and from the human and system without imposing undue cognitive effort on the operator in translating the information. There are many other general human factors interface design principles for complex systems that may have applicability to interfaces for AA, including, for example, the list provided by Noah and Halpin (see Rouse, 1988). However, what is needed at this point are high-level and specific interface design recommendations that are presented in the context of systems to which AA is most common, such as aircraft.

3.1. AA and Cockpit Interfaces

Although aircraft systems currently support a crude level of AA (pilots may shift between manual and automated control at will), a number of problems with this process have been noted. For instance, today's automated flight management systems do not adequately support pilots in coordinating between information meant to support manual flight and that meant to support automated flight (Abbott, Slotte, & Stimson, 1996). For example, the American Airlines Flight 965 aircrew that crashed in Cali, Columbia, in 1995 was forced to struggle with paper maps and displays that used different nomenclatures and provided different reference points, making it very difficult to coordinate between manual and automated operations (Endsley & Strauch, 1997). They furthermore had only partial information provided through any one source and, therefore, were required to integrate cryptic flight plan information in working memory. These discrepancies leave pilots faltering in trying to work with systems that do not support their operational needs. The systems interfaces are poorly designed in terms of providing the SA needed for understanding the behavior of the aircraft in automated modes, and predicting what a system may do in any given situation has proven erratic. Attempts by pilots to make dynamic shifts in LOAs in situationally appropriate ways have been shown to be fraught with problems (Air Transport Association, 1999; Endsley &

Strauch, 1997), and aircraft interfaces do not allow pilots to track shifts and to effectively and efficiently adapt to them.

At a very basic level, system displays for supporting manual and automated control need to be consistent and coordinated to allow smooth transition from one mode of operation to another. In the context of aviation systems, Palmer, Rogers, Press, Latorella, and Abbott (1995) stated that interface design should

1. Foster effective communication of activities, task status, and mission goals, as well as the development of useful and realistic conceptual models of system behavior.
2. Enhance operator awareness of his or her own responsibilities, capabilities, and limitations, as well as those of other team members.
3. Support DFA that is quick, easy, and unambiguous.

The latter recommendation is directed at AA and supporting pilot performance when shifts in LOAs occur. These are important recommendations because the way in which an interface presents information to the user will impact what is perceived, how accurately information is interpreted, and to what degree it is compatible with user needs or models of task performance (all of which may critically influence operator development of good SA on modes of operation of a complex system).

Unfortunately, the application of AA to complex systems like aircraft often increases rather than decreases the amount of information an operator must perceive and use for task performance, including data on system automation configuration and schedules of control function allocations. On the basis of Palmer et al.'s (1995) recommendations, interfaces for AA must support integration of such data regarding "who is doing what" with task-relevant data. And they should ensure that all information is presented in a cohesive manner; therefore, function allocation information should have meaning to current task performance. For example, aircraft automated vertical flight control modes should provide guidance on the operation of different types of speed control (e.g., speed controlled via elevators with maximum thrust or idle thrust) and altitude control (e.g., vertical speed or altitude controlled via the elevators and speed controlled via throttles) on the basis of current phase of flight and current flight segment, as well as the current LOA for flight control (Feary et al., 1998).

In addition to these, interfaces are needed to facilitate the development of strong mental models regarding how such a complex system will function across many classes of situations. Lehner (1987) stated that accurate mental models are important because HCI can remain effective even when there is significant inconsistency between the problem-solving processes of the human and the decision support system, although system error conditions may occur in which recovery is only possible by one method of operation. Cockpit interfaces for supporting mental models of automated systems in aircraft operations have been found to be very poor, leading to significant difficulties in understanding system behavior (McClumpha & James, 1994; Wiener, 1989).

In particular, mental model development can be affected by system response feedback on a user's actions through an interface in addition to consistently displayed system state information. Feedback allows the operator to evaluate the system state in relation to his or her control actions, goals, and expectations of system functioning. Both individual and team feedback of knowledge of system states and responses have been shown to optimize human-machine performance (Krahl, LoVerde, & Scerbo, 1999). Lack of feedback forces the human into an open-loop processing situation in which performance is generally poor (Wickens, 1992).

Although the need for good SA and good mental models are fundamental to the operation of automated systems in general, achieving them can be even more challenging with the added complexity of AA. System interfaces need to support the understanding of not just one system, but multiple systems, in that at different levels of AA, the system may operate in very different ways.

3.2. Dynamic (Cockpit) Displays For AA

Morrison, Gluckman, and Deaton (1991) also raised general interface design issues that should be considered when implementing AA in the airplane cockpit. They stated that automated tasks may require new interfaces and cues so that (a) the status of the automation is clearly indicated to the human, (b) effective coordination of task performance is facilitated, (c) monitoring of the automated task by the human is encouraged, and (d) manual performance of the task after automation is not negatively affected. These interface characteristics are similar to the design recommendations made by Palmer et al. (1995). Unfortunately, they do not offer specific interface design guidelines for AA. However, like many other AA researchers, Morrison et al. are proponents of using adaptive interfaces, or displays that change dynamically, according to changes in AA control allocations to ensure the effective coordination of task performance.

Introducing dynamic displays into adaptive system interface design is currently a critical research issue. Dynamic displays can allow for consideration of operator information requirements as well as styles of interaction through their configuration. For example, dynamic displays implemented in the aircraft cockpit can present specific interface features based on different modes of automated flight and functional roles of pilots under different modes. They can also allow pilots to select or deselect features according to their individual information needs and styles of flying the aircraft (Wiener, 1988). By allowing for flexible configuration of displays and meeting pilot information requirements, SA may be enhanced and performance made effective across modes of aircraft operation.

Dynamic displays have, however, been noted to cause human-machine system performance problems depending on how they are implemented. If dynamic displays are optimized to include just the information that supports a particular mode of operation, the global SA that is needed to support operators' knowledge of when to switch modes may be lacking. That is, they also need information that will alert them to the need to switch from automated to manual control and the information that will support such a transition smoothly. Display interfaces that are optimized for automated control may lack sufficient information to allow operators to build up this level of understanding. The same can be said of the transition from manual to automated control, although this may not be as difficult. Norman (1990) noted that designers often leave critical information out of automated displays in the belief that operators no longer need that information.

From the opposite perspective, Wiener (1988) pointed out that there is a potential toward display clutter and ill-considered symbols, text, and color in many dynamic display designs for complex systems. This is brought about by the designer attitude that if it can be included in the interface, then it should. This approach to interface design strays from the theory of human-centered automation (Billings, 1997). A number of AA research studies have been conducted to establish interface design approaches to address this tendency. For example, direct manipulation interface design was proposed by Jacob (1989) as an interface style for use in AA systems to offset some performance disadvantages associated with dynamic dis-

plays that are linked to different modes of automation and to address the lack of transparency of system functions through interfaces under high LOAs. The lack of function transparency has been associated with mode awareness problems (Sarter, 1995).

Ballas, Heitmeyer, and Perez (1991) studied the direct manipulation interface style to determine whether it would be particularly effective in an intelligent cockpit implemented with AA. Two important components of direct manipulation that were anticipated to improve performance included (a) reduced information processing distance between the users' intentions and the machine states and (b) direct engagement without undue delay in system response and with a relatively transparent interface. Ballas et al. found that using direct manipulation and maintaining a consistent interface style could offset the negative effects of changing controls and displays (dynamic displays). They also speculated that direct manipulation would enhance SA in assessment tasks in particular, and, consequently, have the potential to reduce automation and dynamic display-induced performance disadvantages.

In support of these findings, other research has shown that adaptive systems providing indirect manipulation and opaque interfaces have negative effects on human-computer communication and overall system performance, as they may restrict human interaction with the system (Scerbo, 1996). Sarter and Woods (1994) observed an automation opacity problem with adaptive systems and claimed that user data interpretation becomes a cognitively demanding task rather than a mentally economical one.

On the basis of this research in the context of adaptive systems, Scerbo (1996) encouraged designers of interfaces for AA to include as many information formats as possible to allow data to flow more freely between the human and system. In this way, operators may be able to communicate more naturally because information translation would not be limited to one or two formats. However, it is important to ensure that multimodal interface capabilities of contemporary, complex systems are not exploited to the extent of causing information overload, as previously observed by Wiener (1988) in historical dynamic displays.

3.3. Summary of Interface Design Research For AA

Some general guidelines for AA have been presented in context, but they do not offer the specificity needed to fully support design. Further applied work is needed in this area to evaluate the degree to which the designs of dynamic displays support human performance without increasing cognitive and perceptual loading. In addition, work should be done to explore the effects of using multiple display formats, as some researchers have suggested, for meeting specific operator information requirements and simultaneously ensuring global awareness of system states and changes among modes of operation. In particular, careful attention needs to be paid to the extra demands associated with detecting the need for, and effecting, smooth transitions between AA modes.

4. AA AND HCI

Communication is a critical factor in achieving effective human-automation integration. Most researchers agree that effective communication among complex system components is critical for overall system success (see Scerbo, 1996). This is due to each individual component or member of the system (the human or computer) possessing knowledge and information that other members may not. Thus, each member must share information to make decisions and carry out actions.

Within the context of human–human teams, this need has been termed *shared SA*. Shared SA is defined as the degree to which team members have the same awareness of information requirements for team performance. It is related to team SA, which is “the degree to which each team member has the information needed for his/her job” (Endsley & Jones, 1997, p. 47). Shared SA incorporates not only information on system states, but also the effect of task status and actions of other team members on one’s own goals and tasks (and vice versa) and projections of the future actions of other team members. For a human–machine team, the same need exists. The machine will have certain expectations of human behavior built into it and needs to ascertain what actions have or have not been taken in relation to its programming. The human operator needs to have an understanding of not only what the machine has done, but also what it is doing and will do next. Failures in this shared SA among humans and machines are well documented (Wiener, 1989).

The tendency for sharing of information between parties may change with changes in system function allocation and LOAs associated with AA. This must be considered in AA design and interface design. The question can be raised as to whether the human operator will be able to continue communicating with automation effectively without performance implications when the mode of system automation changes dynamically, regardless of the quality of the interface design. The mode of system automation, the structure of the operator’s role, and operator workload may inhibit critical information flow and, in the worst case, only allow the human to observe the system. Because of the manner in which automation is structured in a supervisory control system, human operators are not permitted involvement in active decision making on a routine basis during system operations. Process control interventions can be used for error prevention, but they do not provide for regular communication between the operator and system automation. This is unlike other forms of automation, such as batch processing systems, where operators are involved in active control of the system and communicate with the automation in planning and decision-making tasks on a regular basis, although the communication may be related to future processes. Active versus passive decision making has been identified as a critical factor in operator out-of-the-(control) loop performance problems, including a loss of SA (Endsley & Kiris, 1995). Under supervisory control, operators are normally provided with high-level summaries of system functions handled by automation (Usher & Kaber, 2000). This form of feedback may be sufficient for monitoring the safety of system states, but it is usually inadequate for decision making toward planning operations and so forth. This problem extends beyond interface design as it is rooted in the adaptive structuring of the system and the natural behavior of human operators, although it may be affected by interface design changes. Research needs to identify how effective human–automation interaction can be maintained across LOAs regardless of changes in the role of the operator in order to promote SA and performance when DFAs occur.

4.1. Establishing a Human–Automation Relationship and Potential Problems

To ensure effective human–automation communication under AA, Bubb-Lewis and Scerbo (1997) said a working relationship between the human and the system must be developed. Muir (1987) offered some suggestions for developing this relationship in adaptively automated systems, including providing operators with information such as the machine’s areas of competence, training operators in how the system works, providing them with actual per-

formance data, defining criterion levels of acceptable performance, and supplying operators with predictability data on how reliable the system is. Also, appropriate feedback mechanisms and reinforcement during training are important ingredients in developing a relationship and creating an effective human–computer team.

Key problems in training and performance that can serve to undermine the human–automation relationship and interaction under AA include human information misinterpretation. This problem may stem from the inability of the human to assess the intention of the computer system (Bubb-Lewis & Scerbo, 1997; Mosier & Skitka, 1996). As a result of these misinterpretations, Suchman (see Bubb-Lewis & Scerbo, 1997, p. 96) claimed that systems can lead humans “down the garden path,” sometimes never reaching a solution. To prevent this type of problem, Woods, Roth, and Bennett (1990; also see Bubb-Lewis & Scerbo, 1997) suggested presenting the machine’s current state, goals, knowledge, hypotheses, and intentions to the human in a clear and accurate manner. They stated this will serve to improve human–machine communication and prevent potential information misinterpretation. Beyond this, it must be ensured through the training process, and on the basis of knowledge of system performance data, that operators develop accurate, general mental models of systems and that they are capable of developing up-to-date situational models of the dynamic behavior of a system during operation. In addition to its state, they need to understand what it is doing and comprehend and project what it will do (all three levels of SA). Therefore, in designing training protocols for creating effective human–automation relationships in complex systems control, it may be necessary to capture SA requirements (Kaber & Endsley, 1997) to facilitate situational model development and support accurate mental model formulation.

The success of this approach may, in fact, be dependent on the system interface design to some extent and is the real goal of design efforts. Although it is easy to state that such information is needed by operators, ensuring that it is provided to them through automation and interface design has proven more elusive. One approach toward creating system interfaces that support operator SA needs involves interface design based on a detailed analysis of the system information, comprehension, and projection requirements of the human operator (Endsley, 1996; Usher & Kaber, 2000). An example of such an analysis for aircraft systems is provided in Endsley, Farley, Jones, Midkiff, and Hansman (1998). Based on this analysis, which is focused around operator goals, the information that is needed to support decision making in both manual and automated control modes can be derived and applied to support design efforts.

4.2. Consistent Versus Dynamic Approaches to HCI Styles Under AA

In addition to developing a working relationship and facilitating information sharing, determining how HCI will occur under DFA is critical to adaptive system performance. Studies of performance, SA, and workload effects of AA have observed successful human–machine system performance under various AA strategies blending the human operator and automation in different ways (LOAs) over short and long task durations with a common mode of interaction (Kaber & Endsley, 1997; Parasuraman et al., 1996). This finding is most likely due to the experimental system interfaces being designed to support all system functions assignable to the human operator under any degree of system autonomy. This type of design may support performance, but it also necessarily increases interface information density and op-

erator attentional resource load. It does not optimize human–machine system interaction for a particular mode of operation. Modes of interaction customized for DFAs should not only support operators in all potential roles, but also should optimize the information exchange between the human and system.

Conversely, others have noted situations where a consistent interaction style across modes of automation may negatively impact performance. According to Sarter and Woods (1995), common human–automation communication in the “glass” cockpit of an advanced commercial aircraft involves the pilot interacting with the flight control panel to enter a desired vertical speed or flight path angle. Although these two flight parameters have different units (feet per minute vs. degrees), they are entered via the same control knob, and the interpretation of the displayed value depends on the active mode of automation. The pilot needs to remember the characteristics and cockpit indicators of each mode, be aware of the current active mode to properly interpret the flight parameter value, and know the possibilities and implications of his or her operation on the control panel. Mode-awareness problems are common with these designs, as pilots must operate the system in different automation modes.

To prevent the potential for mode confusion and information misinterpretation, the design of the automated systems should support intuitive, mentally economical comprehension of the active mode (Sarter & Woods, 1995) by uniquely characterizing it and displaying details on the system configuration, such as flight parameter units. This is important because in many systems certain LOAs (e.g., supervisory control) that involve human monitoring of dynamic subsystem functioning during the majority of task performance may allow for the state and behavior to be altered independent of any human activity. If the human is not tracking changes in the mode configuration of the system or is not informed of automation changes via an effective interface, a breakdown in operator communication with the system may occur, along with errors in operator SA. This can have serious implications for human–machine system performance. For example, operators may fail to intervene in system control loops when an interface, or system behavior, suggests some type of failure has occurred (Endsley & Kaber, 1999; Endsley & Kiris, 1995). Or the operator may attempt an input action that is inappropriate for the current system state or mode of automation.

With this sense of the potential performance issues associated with shifting between modes or LOAs while using a common approach to HCI, it is important to consider empirical AA research on changes in HCI styles with DFAs during complex systems performance. Small (1995) offered that information exchange mechanisms that vary with changes in operator roles in system control and information needs are requisite to AA. Therefore, the form of communication between the human and computer must change, in particular the features of interfaces displaying information. A real-world example of a system capable of this is the Information Manager initially proposed by Geddes and Hammer (see Duley, Mollo, & Parasuraman, 1997), which allows for aircraft cockpit controls and displays to be intelligently configured to provide task-relevant information to pilots on flight plans and automation subsystem events.

A major limitation of such systems is that they purport to know just which information operators really need. Such approaches to information filtering may actively deprive operators of global SA that is needed for them to effect smooth and timely transitions to new goal states and operational modes (Endsley & Bolstad, 1993). Another drawback of this method of adapting mechanisms of human–computer communication to automated system states is

that human operators must develop effective strategies of divided attention allocation. Adaptive interfaces may capture operator attention by regularly introducing new or dishabituated stimuli while information attended to previously (habituated stimuli) may be neglected (see Cowan, 1988). Operators must be able to effectively distribute their attention across all task-relevant information while using these devices to ensure successful performance. In addition, systems such as this act to provide the operator with a new source of information that must be taken in and integrated with other system information. This can create additional workload for the operator and may slow performance rather than aid it.

In a study conducted by Duley et al. (1997), an integrated display (EMACS) and nonintegrated display (EICAS) were contrasted to investigate the effects of the abrupt appearance of new task information due to a change in automation of the underlying system. Participants performed simulated aircraft flight tasks, including tracking, fuel management, and engine monitoring manually, followed by automation of the monitoring task, which required them to detect system automation failures. They found significantly decreased performance in deviation detection in the engine-monitoring task using the integrated display under the dynamic display condition as compared to a static presentation (i.e., when automation was applied vs. completely manual control). Duley et al. inferred that participants did not allocate sufficient attentional resources to the monitoring task when it was presented through the integrated display. For the nonintegrated display, significant improvements in response time to automation failures were observed under the dynamic presentation condition (AA) as opposed to the static display method (manual control). These findings are in contrast to the results of previous studies, in which integrated displays have been found to support pre-attentive information processing in automation monitoring. On the basis of these findings, Duley et al. noted that external attentional guidance might be necessary when using dynamic presentation of integrated displays to ensure effective operator performance. Based on this work, appropriate methods of HCI under AA may require the system to manage information according to operator task requirements and to provide interface features to dictate attentional strategies.

4.3. General Recommendations on Structuring Human–Automation Interaction in Adaptive Systems

To deal with the potential for operator lack of mode awareness in controlling adaptive systems, three recommendations can be made for improved structuring of HCI. First, as previously advocated, adaptive system states should be made transparent to operators. Secondly, Sarter (1995) recommended external attentional guidance be facilitated for users through timely salient system indicators to enable them to project future system states particularly in circumstances when system behavior may be unclear. For example, under unanticipated automated subsystem failure or error conditions, immediate error feedback or messaging and salient presentation of visual or auditory cues related to the error can capture an operator's attention, allowing for timely diagnosis and corrective action. Based on the understanding they develop of the problem, operators may be able to make future projection of system status and behavior. External attentional guidance can also be used in adaptive systems with silent behavior (mode transition without salient signals). It may also serve to prevent ineffective operator divided attention strategies to adaptive dis-

plays, including new and historical data, and aid them in perceiving task-critical information under all modes of system automation.

Thirdly, interfaces must be designed with the understanding that they need to support manual performance, automated performance, and effective transition between these states. This last factor is crucial to successful AA and is often not supported in today's systems. Effective transition between manual and automated modes (when transition is manually controlled) requires displays that make salient the need for automation or manual control based on workload considerations and system capabilities and environmental demands. Operators need to be provided with information to determine when they are operating at their own limits or at the limits of the capabilities of automation. This information is not always clear in today's systems (Air Transport Association, 1999). If transitioning to manual control, operators need to be provided with an in-depth understanding of the state of the systems the automation has been controlling so that they are not suddenly thrust into a situation of which they have a shallow or erroneous understanding. If transitioning to automated control, they need to be provided with information on how well the system has picked up its new responsibilities. For this transition to occur smoothly, this information is needed *before* the transition occurs, so that operators are prepared and not left trying to correct difficult situations after they get into them. At a minimum the displays and information sources that support transitioning between different modes need to be consistent and, if at all possible, integrated to reduce the problems associated with making the transition.

5. AA AND CREW INTERACTION

The introduction of AA in dynamic complex systems not only can affect the interaction between the human operator and machine, but it may impact the social interactions of human operators, such as flight crewmembers in an aircraft. Norman (1990) pointed out that crew coordination among pilots is supportive of vigilance and SA and may lead to improvements in system status monitoring and early detection of system performance deviations from desired levels. Petridis, Lyall, and Robideau (1995) offered that the key element of effective complex system performance is crew coordination through (verbal) communication.

5.1. Verbal Communication

AA may radically and qualitatively alter the communication structures between humans in controlling complex systems. Using the example of aviation automation, as noted by Wiener (1985), mounting evidence shows that crew coordination and interaction in advanced automated commercial aircraft cockpits are qualitatively different than in the traditional aircraft cockpits. In highly automated aircraft like the Boeing B-757 or McDonnell Douglas MD-11, the electronic systems have become prominent team "members." Humans and the machine must work together closely as partners to maintain optimal operation of the system under high LOAs (Scerbo, 1996). There is an increase in the requirement for operators to actively interact with automated systems in operations such as programming the system for control allocations via dynamic data entry and interfaces (Bowers, Oser, Salas, & Cannon-Bowers,

1996). This has had a significant impact on human–human interaction; specifically, verbal communication may occur at lower rates (see Bowers et al., 1996).

Another characteristic of such systems potentially limiting human–human interactions during most operations is that automated systems often have critical information needed by operators to assess situations and make decisions. Therefore, system information can usually be collected by operators without vocal communication among each other (Mosier & Skitka, 1996), possibly inhibiting effective crew coordination. Lower levels of communication among crewmembers may be directly due to the workload associated with manipulating and operating the automated system. Costley, Johnson, and Lawson (1989) found less crew verbal communication due to advanced cockpit automation. In addition, they also noted that crewmembers were apt to communicate via automated systems instead of person-to-person. For instance, pilots of commercial aircraft may select speed targets by using the flight control panel, allowing a copilot to observe this intention through the speed display window on the panel and essentially precluding the need for them to communicate on the target verbally.

Contrary to these observations, Straus and Cooper (1989) found that verbal communication was more prevalent among flight crews under automated conditions. In general, heterogeneous aircrews (composed of one highly experienced pilot and one less experienced pilot) communicated more often on task-related issues under automated conditions, whereas homogeneous aircrews (composed of equally experienced pilots) engaged in more task-relevant communication in manual modes. Therefore, human task experience may interact with the implementation of AA to impact crew coordination. Straus and Cooper also found that more task-related communication resulted in better pilot performance, as projected by Norman (1990).

Because AA is intended to assist system operators by dynamically distributing workload between them and machines (Duley et al., 1997), its implementation should theoretically moderate operator workload, and these savings in cognitive resources should permit operators to communicate more frequently toward effective coordination and system performance. However, instead of permitting more effective team planning and coordination, an increased frequency of verbal communication among pilots (especially heterogeneous aircrews) might pose an additional cognitive load for tasks such as aiding each other in interacting with automated systems (see Billings, 1997). This could be a particularly critical issue in systems providing a number of modes of automation. As an example of the impact of automation on the frequency of crewmember communication, the aircrew in the American Airlines incident in Cali, Columbia, communicated continuously toward resolving a flight management system programming problem. Unfortunately, the interface did not support them in providing the information needed to detect their unsafe situation (Endsley & Strauch, 1997). Several studies (see Petridis et al., 1995) indicate that system performance is not simply associated with the quantity of human–human communication but the timing and quality of that communication. Wiener (1989) surveyed pilots as to the impact of automated flight systems on crew communication performance. They reported difficulty in delegating programming and monitoring responsibilities among crewmembers. However, automation was considered helpful in permitting communication during flight control panel monitoring. It might not be the case that providing some form of automation all the time necessarily improves operators' coordination as it may result in unintended consequences of interfering with crew communication and coordination in critical tasks, as observed by Wiener (1989). With this in mind, AA blending manual control in automated flight modes

may be required at specific times in flight operations to prevent communication breakdowns leading to performance problems (see Bower et al., 1996).

5.2. Nonverbal Communication

Segal and Jobe (1995) made similar observations to Wiener (1989) that cockpit automation (in general) made it difficult for flight crews to communicate nonverbally, specifically to observe the actions of each other (e.g., the copilot's view of the pilot in programming the flight management system may be obstructed) due to the design of the flight deck layout. According to Segal and Jobe, pilots monitor actions of each other and make use of gestures with the knowledge that crewmembers see and understand them. This serves as an important nonverbal source of information because visual information (e.g., pushing knobs and buttons, moving throttles) can support and enhance speech communication (Bowers et al., 1996). Segal and Jobe also observed that automation created new task demands for crews that limited interaction during certain system operations. They noted that automated systems have the potential to modify or alter the nature of nonverbal information available to flight crewmembers, for example, by simply reducing the control actions of operators (see Bowers et al., 1996).

Related to this research, some automation interfaces allow one crewmember to give instructions to the system without permitting the other to infer the nature of the input from observable behavior alone (Sarter, 1995). This may compromise nonverbal communication and isolate operators from each other's situation assessment and decision-making processes and responses, thus increasing the possibility of errors in crew coordination and flight performance (Mosier & Skitka, 1996). To combat these problems, many airlines have instituted procedures to specifically communicate information on flight management system programming and changes in flight management system status; however, breakdowns in such procedures are not uncommon.

Nonverbal communication and interactions with the equipment may have a more subtle effect on complex system performance than direct verbal communication (Bowers et al., 1996). Breakdowns of either form of communication in the cockpit due to automation may cause serious performance consequences and must be considered in adaptive system design. A lack of human-human interaction in controlling complex systems over long durations may ultimately result in operators developing different, and probably conflicting, strategies for accomplishing tasks (Sarter & Woods, 1995) that are critically lacking in crew coordination. Consequently, methods and goals may not be shared among crewmembers, and SA and performance may be compromised.

Although these issues are present in the control and design of automated systems in general, their effects in systems employing AA cannot be overlooked. Very little is known, however, regarding the degree to which AA may exacerbate or ameliorate the effects of automation on human-human interaction.

6. SUMMARY

We presented a review of literature on issues in the implementation of AA and related the work to the objectives of a theory of human-centered automation. Automation research has yet to define optimal strategies for AA across a broad spectrum of systems. We believe the hurdles to this goal include the following:

1. Designing appropriate mechanisms for human–machine communication in adaptive systems.
2. Structuring human and computer communication in adaptive system control to ensure effective performance under any mode of automation.
3. Designing AA to support crew communications for team coordination.
4. Designing AA to consider operator workload in function allocation management and system and task responsibilities.

We have already identified some research needs with respect to these issues. Here we summarize the issues collectively and identify additional important directions of research. Table 1 also provides a concise summary of the general empirical and analytical research observations on the issues associated with the implementation of AA in complex systems that were reviewed in this article. With respect to system interface design and AA, some general interface design guidelines have been put forth for adaptive systems, but they have little utility to specific tasks. On this basis, empirical studies have been conducted to evaluate dynamic displays linked to changes in adaptive system function allocation for supporting human performance. Although such displays have been anticipated to reduce operator cognitive and perceptual load by providing what information is needed when, the opposite seems to have occurred in some systems in that through the interface development process any and all information on the system that can be included has been, and displays are cluttered and difficult to use. In other cases, needed information is sorely lacking, and system status is quite problematic.

With this problem as motivation, other empirical studies have examined performance effects of interfaces to adaptively automated systems that use a consistent style regardless of the LOA but that provide operators with direct control of system functions and make automation states transparent to users. This type of interface has shown promise over those providing indirect control filtered through computer systems, which are more vague in their presentation of automation states. Further applied work is needed in this area. Some researchers have suggested using a combination of formats and possibly leaving the problem for users to resolve; however, this only sweeps the problem under the rug and waits for errors to occur in the field, only to be blamed on the operator.

In terms of human–computer communication under AA, research has pointed to a lack of operator awareness of the mode of automation due to the states, intentions, and actions of computer control not being predictable or clearly communicated to the human. We reviewed literature identifying the need for a relationship to develop between humans and automation to address this type of problem at a basic level. Like research on interface design for AA, studies also identify system automation transparency as the key to improving operator mode or SA. This work has also advocated dynamic displays that meet operator information requirements under various modes of automation. The critical issue associated with both of these initiatives is designing interfaces that do not pose high information processing loads on operators in terms of data perception and translation due to high information density and that actually meet operator SA requirements.

With respect to the effect of adaptive system automation on human crew interactions, complex observations have been made through both analytical and empirical studies. A key finding is that the capability of flight crews to communicate electronically through automated systems seems to have subtracted from crewmember verbal communication. In gen-

TABLE 1
Summary of Research Observations on Implementation Issues for AA in Complex Systems.

<i>Research Issue</i>	<i>General Findings</i>	<i>Supporting References</i>
Workload and AA	<ol style="list-style-type: none"> 1. Workload increases due to monitoring load associated with tracking function allocations. 2. Workload increases due to requirement on human to manage function allocations. 	<p>Endsley (1996); Kaber & Riley (1999); Scerbo (1996)</p> <p>Kaber & Riley (1999); Selcon (1990)</p>
Interface design for AA	<ol style="list-style-type: none"> 1. Interfaces do not adequately support shifts between manual and automated control. 2. Human control of DFA in adaptive systems is problematic because interfaces do not adequately support SA. 3. Interface design does not support good mental model development and leads to difficulty in tracking/understanding system behavior. 4. Dynamic displays must present information relevant to each mode of system operation and information to facilitate global SA for effectively switching modes. 5. Caution must be exercised in dynamic display design to avoid inclusion of all potential data, but information that supports SA. 6. Direct-manipulation interfaces may offset negative human performance effects associated with changes in system modes and interface features. 7. Opaque interfaces negatively effect HCI and overall system performance. 8. Interfaces should include multiple information formats to allow efficient human-system data exchange while also considering information overload. 	<p>Endsley & Strauch (1997); Abbott et al. (1996)</p> <p>Air Transport Association (1999); Endsley & Strauch (1997)</p> <p>McClumpha and James (1994); Wiener (1989)</p> <p>Norman (1990)</p> <p>Wiener (1988)</p> <p>Ballas et al. (1991); Jacob (1989)</p> <p>Scerbo (1996); Sarter & Woods (1994); Ballas et al. (1991)</p> <p>Scerbo (1996); Wiener (1988)</p>
HCI in adaptive systems design	<ol style="list-style-type: none"> 1. Information must be shared among human-machine teams during system operations to prevent shared SA failures. 2. Structure of AA may dramatically change operator's role from active control to passive monitoring and contribute to loss of SA. 3. Effective relations must develop between human and automation to facilitate communication in system operations. 4. Human misinterpretation of information due to inability to assess system state undermines human-automation relationship. 	<p>Endsley & Jones (1997); Wiener (1989)</p> <p>Endsley & Kiris (1995); Usher & Kaber (2000)</p> <p>Bubb-Lewis & Scerbo (1997); Muir (1987)</p> <p>Mosier & Skitka (1996); Bubb-Lewis & Scerbo (1997)</p>

(continued)

TABLE 1 (Continued)

	5. Present machine-state, goals, knowledge, hypotheses, and intentions to improve communication and operator mental model of system.	Bubb-Lewis & Scerbo (1997); Woods et al. (1990)
	6. Consistent interface style across modes of AA supports operator SA and overall performance, but may increase display density.	Kaber & Endsley (1997); Parasuraman et al. (1996)
	7. Inconsistent HCI styles across modes of AA may lead to mode awareness problems due to alternate uses of interfaces across modes.	Sarter & Woods (1995)
	8. AA interfaces must support operator mode comprehension as system states may change independent of human activity and operators may fail to intervene in system control when needed.	Endsley & Kaber (1999); Endsley & Kiris (1995); Sarter & Woods (1995)
	9. Provide salient visual and auditory cues through AA interfaces to capture or guide operator's attention to system state indicators.	Duley et al (1997); Sarter (1995)
AA and crew interaction	1. Workload associated with operating highly automated systems has significantly reduced human-human interaction.	Bowers et al. (1996); Costley et al. (1989); Wiener (1985)
	2. Human crewmembers are apt to communicate via automation interfaces instead of verbally when controlling highly automated systems.	Billings (1997); Bowers et al. (1996); Costley et al. (1989)
	3. Heterogeneous human crews communicate more under automated control conditions (experienced operators instruct novices).	Petridis et al. (1995); Straus & Cooper (1989)
	4. Timing and quality of human-human interaction in adaptive systems control are critical to system performance.	Petridis et al. (1995); Wiener (1989)
	5. Nonverbal communication is a critical source of information in automated systems for supporting shared SA and crew coordination.	Bowers et al. (1996); Mosier & Skitka (1996); Segal & Jobe (1995)

Note. AA = adaptive automation; DFA = dynamic function allocations; SA = situation awareness; HCI = human-computer interaction.

eral, future work is needed to identify critical crew interactions in complex adaptive systems and to design AA strategies to support them.

We also reviewed literature related to operator workload in adaptive systems; particularly those in which the human is assigned the responsibility of managing control function allocations and to complete system tasks at the same time. Unfortunately, in designing AA strategies most research has not considered the additional workload imposed on operators in interacting with computer systems to manage DFAs. For AA to be effective in terms of workload moderation, this must be a concern in the design of future adaptive systems.

This understanding of workload interface design and communication issues related to AA can be organized in the theoretical framework of human-centered automation development in the engineering psychology literature, which already includes a detailed description of strategies to AA, methods to triggering dynamic control allocations in adaptive systems, who should be in charge of adaptive systems (the human or computer), and so on. Future reviews and empirical studies should be conducted with the objective of supporting a comprehensive theory of human-centered automation to optimize human-machine system performance, operator SA, and workload in the implementation of AA.

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