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ADAPTIVE AUTOMATION

Current Status and Challenges

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ABSTRACT

Adaptive automation (AA) is the dynamic, real-time change in the degree of automation (DOA) triggered by conditions such as poor task performance and high operator workload. AA has been discussed in the literature as a promising means of mitigating human performance issues that often arise in highly automated systems, such as loss of situation awareness, complacency, and degrading of manual skills. The purpose this study is to define the current state-of-the-art in AA research and application and to examine its use in the commercial nuclear industry. We reviewed published literature and obtained information from automation subject matter experts. We also conducted a site visit to a nuclear plant designer that is developing AA systems. The results were organized into the following topics: Effects of AA on performance, human-automation interaction and human-system interfaces (HSI), and human factors engineering (HFE) guidance for designing and evaluating AA systems. In general, we found that AA improved task performance and the operator's understanding of automation. While the research is limited, AA also supported operator recognition of automation failure and recovery. The design of HSI for AA systems is a key consideration. An important aspect of HSIs is the design of how AA interacts with operators. AA systems are more effective when they follow rules of etiquette similar to those used by human crewmembers in the operational environment. There is limited HFE guidance available to support designers and reviewers of AA systems. While standards and guidelines acknowledge AA as a design option, relatively few guidelines are available to support the function allocation process or the detailed design of the key aspects of AA systems. Based on our findings, we have identified future research and development needs.

This RIL should be used as a companion piece to a previous report by O'Hara & Higgins, 2017 (Technical Report No. D0013-2-2017), with the same title, that was developed into RIL 2020-06. The results of this report were used heavily in the conclusions for RIL 2020-06.

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ABBREVIATIONS AND ACRONYMS

AA	adaptive automation
ABWR	Advanced Boiling Water Reactor
AFCS	automatic flight control system
ATC	air traffic control
CBP	computer-based procedure
CIM	Cockpit Information Manager
ConOps	concept of operations
COSS	computerized operator support systems
D	divergence
D/F	degradation and failure
DOA	degree of automation
DoD	Department of Defense (U.S.)
DOE	Department of Energy (U.S.)
ECAM	electronic centralized aircraft monitor
ECG	electrocardiogram
EdF	Électricité de France
EEG	electroencephalogram
EID	ecological-interface design
EOG	electrooculograph
EPRI	Electric Power Research Institute
FA	function allocation
FAA	Federal Aviation Administration (U.S.)
FITNESS	Functional Integrated Treatments for Novative Ecological Support System
FMS	flight management system
F/T	functions and tasks
GE	General Electric
HFDS	Human Factors Design Standard
HFE	human factors engineering
HFES	Human Factors and Ergonomics Society
HSI	human-system interface
I&C	instrumentation and control
IAI	intelligent adaptive interface
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IFM	intelligent fault management
ISO	International Organization for Standardization
ISV	integrated system validation
LOA	level of automation
NASA	National Aeronautics and Space Administration (U.S.)
NEA	Nuclear Energy Agency
NPICHMIT	Nuclear Plant Instrumentation, Controls and Human-Machine Interface Technologies
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission (U.S.)
NTSB	National Transportation Safety Board (U.S.)
O&M	operations and maintenance
OFS	operator functional state
ONR	Office of Nuclear Regulation (United Kingdom)
PF	pilot flying

PGCS	Power Generation Control System
RPA	Rotorcraft Pilot’s Associate
RVSM	reduced vertical separation minimum (distance)
S&G	standards and guidelines
SA	situation awareness
SMR	small modular reactors
SME	subject matter expert
SSCs	structures, systems, components
TLX	Task Load Index
U.S.	United States
UAV	unmanned aerial vehicle
UGV	unmanned ground vehicle
UV	unmanned vehicle
WGHOF	Working Group on Human and Organizational Factors

1 INTRODUCTION

1.1 Automation and Human Performance in Complex Systems

Technology has been used to replace humans performing tasks since the beginning of the industrial revolution. Early efforts to automate these tasks focused on the physical aspects while the scope of more modern automation has expanded to include the cognitive aspects of tasks as well. Parasuraman and Riley (1997) defined automation as "the execution by a machine agent (usually a computer) of a function that was previously carried out by a human." This definition is often cited and has been adopted in human factors engineering (HFE) standards (e.g., the Federal Aviation Administration's *Human Factors Design Standard*) (Ahlstrom et al., 2003).

In NUREG-0700, Revision 3, "*Human-System Interface Design Review Guidelines,*" (O'Hara & Fleger, 2020) the U.S. Nuclear Regulatory Commission (NRC), uses a variation on this definition – "Automation is a device or system that accomplishes (partially or fully) a function/task." The reference to activities "formerly carried out by a human" has been removed in acknowledgment of the fact that modern systems often have functions or tasks that have been specifically designed for automation with no expectation that human operators would ever perform them as the control system does.

There are numerous reasons for the trend towards increased automation. Historically, one of the compelling reasons has been to improve performance by applying automation to tasks that are difficult for operators to do. The emergence of digital feedwater controls in nuclear plants was just such an application. More recently, automation has been used to achieve a level of performance, control, or precision that is not possible with humans in the loop.

Automation is also introduced to make the human's job easier by lowering human workload. It was believed that by automating difficult, tedious, and time-consuming functions/tasks (F/Ts),[1] operator workload would be reduced. Lowering workload was viewed to enable operators to focus more on overall system performance and improving situation awareness (SA).

Another reason to automate a F/T is to minimize human error. As the design of human-machine systems became more complex, designers often viewed the human as the "weak link;" an unreliable and unpredictable aspect of the system. The solution to making systems more operationally reliable was automation. A prevailing philosophy emerged to automate all F/Ts that could be automated from a technological point of view, leaving people to manage what could not be automated. Automation was viewed to make system performance safer and more reliable.

Another motivation to use automation is to reduce the number of humans needed to operate and maintain a facility. For example, one of the goals of new nuclear power plant (NPPs) designs, such as small modular reactors (SMRs) is to make them more economical in comparison to current plants by reducing operations and maintenance (O&M) cost. O&M costs are significant, and labor is over 50% of that cost (Thomas, 2012). Thomas noted:

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[1] While allocation is typically discussed at the level of functions (e.g., function allocation) functions are hierarchical and can be decomposed into the tasks necessary to perform the function. The allocation of responsibilities to human and automation agents can be at the level of an entire function or the tasks to be performed. To simplify the language, what is allocated is referred to as a function/task (F/T).

> Nuclear power could be at a considerable disadvantage if it continues to rely on an operating model that requires a large plant staff. The largest component of a typical nuclear plant's operating and maintenance (O&M) cost is labor, representing well over 50% of the cost structure. Labor will continue to be a rising cost over time while technology will generally be a falling cost. Thus, generation sources that are more technology-based could significantly erode the cost advantage that the nuclear power industry has enjoyed. Digital technology provides the opportunity to transform the operating model of the nuclear power plants (NPPs) from one based on a large staff performing mostly manual activities to an operating model based on highly-integrated technology operated by a smaller staff. (p. 883)

One approach to achieving Thomas' vision is by increasing automation. O&M costs can be significantly reduced if fewer personnel are needed to achieve production and safety goals. SMR designs are following this approach.[2]

Therefore, there are many reasons designers strive to increase automation employed in complex systems in general and particularly in NPPs.

Modern automation is based on digital technology, advances rapidly, and is increasingly capable. The result being the amount of automation employed in NPPs is increasing and is more broadly applied than it was previously:

- greater use of automation for normal operations, such as plant startup in addition to safety responses
- application to operator aids and decision support, such as to support procedure use and management
- support for interface management, such as automatic display retrieval

Because automation has become ubiquitous in modern control rooms, there are few F/Ts involved in plant operations that are not influenced by it.

With such advances in automation, one might ask whether a need remains for human involvement in day-to-day plant operations. A more suitable role for humans could be high-level supervision and administration of plant functions. While the capabilities of automation may suggest such an evolution of operator roles, in fact, humans are still needed for several reasons. The following are examples of what technology cannot accomplish:

- F/Ts that have such significant consequences, human judgement should be involved
- F/Ts that are too difficult or too expensive to automate
- F/Ts that do not have the technological infrastructure to support automation (e.g., sensors needed to support automation are not available)

Second, humans are needed to handle unplanned and unanticipated events (i.e., situations that arise that were not foreseen by automation/system designers). Third, humans are needed as the last line-of-defense in the face of automation degradations and system failures. With

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[2] It should be noted that the reduction in SMR plant staffing, whether through automation or other means, has been identified as a potential safety issue by the NRC following an Issue Identification and Ranking Program used to independently assess and identify potential technical and regulatory issues (Smith & Moore, 2009) and subsequently in the NRC's report to Congress on advanced reactor licensing (NRC, 2012).

respect to these latter two reasons for maintaining human involvement, the ability to manage situations that are unforeseen by automation designers is seen as providing systems with necessary resilience (Woods & Cook, 2006).

Therefore, humans are still needed for day-to-day operations and to provide overall supervision of plant operation and safety.

1.2 Human Performance Challenges in Highly Automated Systems

With the focus on automation technology, what often gets lost is the human role in the system. Automation designers have not always considered that role, nor have they designed the human-automation interaction to support integrated system performance.

In part, this situation is the result of the approaches used to allocate F/Ts to human and automation agents. At worst, designers take a technological approach to allocation (i.e., they determine where automation can be feasibly applied and cost effective) and whatever is not automated becomes a human responsibility by default. The result is an ad hoc set of F/Ts for operators to perform that may not be suited to their overall responsibilities for system performance and safety or their capabilities.

When human capabilities are considered, they are often evaluated using a "Fitts List" (Fitts, 1951); lists of relative human and automation capabilities. F/Ts are considered in terms of what abilities are needed for a successful performance. The list is then consulted and the F/T allocated to the most capable agent. Such lists are limited because they tend to be overly simplistic and frequently outdated as the capabilities of technology rapidly evolve. Section 7.1 provides a more detailed discussion of Fitts List approaches to function allocation.

Issues associated with failing to account for the human role in highly automated systems were identified in several key papers in the early 1980s (e.g., Bainbridge, 1983; Wiener & Curry, 1980). As research and operating experiences accumulated, it revealed that simply considering whether humans or machines were more capable agents for performing a specific F/T was not sufficient. For example, issues associated with loss of SA became apparent. Endsley (1996) suggested that people are not well suited to monitoring automation. Automation impacts SA in three ways: (1) changes in vigilance and complacency, (2) passive rather than an active role and, (3) changes in the quality of feedback to human operator. Automation's complexity challenges SA, even when personnel attempt to monitor it.

The general issues encountered with highly automated systems are summarized in Table 1-1.

Table 1-1 Human Performance Issues in Highly-Automated Systems

Issue	Key Findings
Human role change	• The notion of simply substituting automation for humans is a myth • Role change is not always for the better (e.g., passive monitoring rather than active control)
Added complexity	• Operator's understanding of automation is incomplete due to increased complexity and its activities were not visible
Monitoring, vigilance, and complacency	• Confidence in automation can lead to complacency and vigilance decrements
Out-of-the-loop unfamiliarity	• Removal from the control loop lowers the operator's situation awareness and alertness • Automation surprises
Skill degradation and loss	• Lack of skills use causes degraded performance
New sources of workload	• Configuring automation • Transitions to manual control
New types of human error	• Mode errors • Errors of commission and omission related to improper assessment of automation's capabilities

In addition to the failure of the F/T allocation process to properly account for the human role in system operations, studies also have shown that a significant contributing factor to the difficulties operators encounter in highly-automated systems is the poor design of the human-system interfaces (HSIs) between operators and automation making it difficult for operators to monitor automation activities and performance (Billings, 1997; Endsley, 1996; Funk & Lyall, 2000; Hollnagel, 1999; Lyall & Funk, 1998; Parasuraman, Sheridan, & Wickens, 2000; Parasuraman & Riley, 1997; Thurman et al., 1977; Wiener & Curry, 1980).

Therefore, the human performance challenges of highly automated systems are well known and have been at least since the early 1980s. It is reasonable to consider whether these issues have been resolved in modern systems (i.e., whether lessons learned from research and operating experience over the past 40 years has led to improvements in human-automation interaction to mitigate the negative effects). However, they have not, and automation still challenges operators. Some recent examples of failures of human-automation interaction illustrate this conclusion.

The 2009 crash of Air France 447[3] typifies many of the problems the crews faced with automation. Airspeed sensor failures led to failure of the autopilot requiring the pilots to take over manual control of the aircraft. The takeover was unsuccessful, and the aircraft crashed in the Atlantic Ocean resulting in the loss of 228 lives.

The official accident report pointed to out-of-the-loop unfamiliarity at the point of manual takeover and a failure to recover SA as the key factors in the crews' failure to manage to situation. In addition, concerns over degradation of manual flying skills in such situations were also noted. The accident report stated:

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[3] https://spectrum.ieee.org/riskfactor/aerospace/aviation/air-france-flight-447-crash-caused-by-a-combination-of-factors

> The occurrence of the failure in the context of flight in cruise completely surprised the pilots of flight AF 447. The apparent difficulties with aeroplane handling at high altitude in turbulence led to excessive handling inputs in roll and a sharp nose-up input by the PF [pilot flying]. The destabilisation that resulted from the climbing flight path and the evolution in the pitch attitude and vertical speed was added to the erroneous airspeed indications and ECAM [electronic centralized aircraft monitor] messages, which did not help with the diagnosis. The crew, progressively becoming de-structured, likely never understood that it was faced with a "simple" loss of three sources of airspeed information. In the minute that followed the autopilot disconnection, the failure of the attempts to understand the situation and the de-structuring of crew cooperation fed on each other until the total loss of cognitive control of the situation. (BEA, 2012, p. 199)

Degradations of manual flying skills in highly-automated aircraft has become such a significant concern that the Federal Aviation Administration (FAA) has issue a Safety Alert for Operators to address it (FAA, 2013). The safety alert summarized the concern as follows:

> Modern aircraft are commonly operated using autoflight systems (e.g., autopilot or autothrottle/autothrust). Unfortunately, continuous use of those systems does not reinforce a pilot's knowledge and skills in manual flight operations. Autoflight systems are useful tools for pilots and have improved safety and workload management, and thus enabled more precise operations. However, continuous use of autoflight systems could lead to degradation of the pilot's ability to quickly recover the aircraft from an undesired state.
>
> Operators are encouraged to take an integrated approach by incorporating emphasis of manual flight operations into both line operations and training (initial/upgrade and recurrent). Operational policies should be developed or reviewed to ensure there are appropriate opportunities for pilots to exercise manual flying skills, such as in non-RVSM [Reduced Vertical Separation Minimum] airspace and during low workload conditions. In addition, policies should be developed or reviewed to ensure that pilots understand when to use the automated systems, such as during high workload conditions or airspace procedures that require use of autopilot for precise operations. Augmented crew operations may also limit the ability of some pilots to obtain practice in manual flight operations. Airline operational policies should ensure that all pilots have the appropriate opportunities to exercise the aforementioned knowledge and skills in flight operations.

Another example of how failures of the human-automation interaction have safety consequences is the 2009 Washington Metropolitan Area Transit Authority Metrorail accident in Washington DC (NTSB, 2010)[4]. The accident occurred when an inbound Metrorail train, number 112, struck the rear of stopped inbound train 214. Nine people aboard train 112 were killed, including the train operator.

The accident had both mode error and degraded system implications. Some of the key findings from the National Transportation Safety Board (NTSB) accident report illustrate these issues:

- The operator's decision to operate train 214 (the struck train) in manual mode during the evening rush hour period was in violation of Metrorail rules, but track circuit B2-304 was

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[4] http://www.washingtonpost.com/wp-dyn/content/article/2009/06/28/AR2009062802481.html

failing to detect trains, regardless of whether they were operating in manual or automatic mode.
- Because train 214, which was being operated in manual mode, was traveling at a much slower speed than the authorized speed commands it was receiving, train 214 stopped completely within the faulty B2-304 track circuit when its detection was lost, and it received a 0 mph speed command.
- The Metrorail automatic train control system stopped detecting the presence of train 214 (the struck train) in track circuit B2-304, which caused train 214 to stop and also allowed speed commands to be transmitted to train 112 (the striking train) until the collision.
- On the day of the accident, parasitic oscillation in the track circuit modules for track circuit B2-304 was creating a spurious signal that mimicked a valid track circuit signal, thus causing the track circuit to fail to detect the presence of train 214.

Automation complexities and the resulting mode confusion it created were at the center of the factors contributing to the crash of Asiana Airlines Flight 214 on July 6, 2013. The Boeing 777-200ER struck a seawall while attempting to land at San Francisco International Airport[5]. Three of the 291 passengers were killed, many others were seriously injured, and the aircraft was destroyed. NTSB (2014) found that the complex design of the automatic flight control system (AFCS) contributed to the pilot's confusion over the failure of the selected mode to control air speed. The pilots believed that the autothrottle was engaged and controlling air speed. However, it was in "hold" mode. Therefore, neither the pilots nor the automation was controlling the airspeed. Thinking the AFCS was controlling air speed, the pilots did not properly monitor the aircraft's airspeed. When they finally realized they needed to abort the landing and initiate a go-around maneuver, the airspeed was not high enough to do so and the crash resulted. The NTSB noted that inadequate training in the complexities of the AFCS and its behavior in different operational modes also contributed to the accident.

The issues identified in these relatively recent accident investigations, such as loss of SA, mode confusion, and skills degradation, are well known and have been for many years. Yet automation systems are still challenging to operators and when issues arise, the consequences to safety can be significant. A similar conclusion was reached in a recent FAA study of flight management systems (Flight Deck Automation Working Group, 2013), leading FAA's Office of Inspector General to recommend increased FAA oversight to reduce issues associated with increased automation (FAA, 2016). While automation technology and capability has rapidly advanced, the technology for human-automation interaction has not kept pace. In all high-risk, high-reliability domains, there is concern as to whether the increased automation will achieve its benefits and minimize potential negative effects on performance and safety

1.3 Prior NRC Research on Human-Automation Interaction

1.3.1 Importance of Automation in the Commercial Nuclear Industry

The importance of human performance in highly automated systems has been recognized in the commercial nuclear industry. In 2007, the Department of Energy (DOE) published a study providing a technology roadmap on instrumentation, control and human-machine interface to support DOE advanced NPP programs (Dudenhoeffer et al., 2007). Seven areas of research were identified as essential elements for advancing these technologies in NPPs. Of those elements, one area of research identified was "Human-System Interaction Models and Analysis Tools:"

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[5] http://aviationweek.com/awin/asiana-crash-puts-focus-training-automation

> This topic addresses the development of new models of human-automation interaction based on emerging control technologies, such as automation that adapts to operator workload. Models should be defined and methods of analysis for allocation of functions, including dynamic allocation, should be formalized. The user interface requirements for each model should be specified. A test program should be included to evaluate concepts.

In 2008, the NRC conducted a study to identify human performance research issues associated with the implementation of new technology in NPPs (O'Hara et al., 2008a & 2008b). To accomplish this, current industry developments and trends were evaluated in the areas of reactor technology, instrumentation and control technology, human-system integration technology, and human factors engineering (HFE) methods and tools. Sixty-four issues were identified. Each of the issues was rated on its safety significance and how soon guidance on the issues was needed to support NRC reviews. The ratings were made by 14 independent subject matter experts representing vendors, utilities, research organizations and regulators. Using the ratings, the issues were organized into four categories with the top category being the most important issues. Twenty of the 64 issues were categorized into the top category, including two related to automation:

- *Levels of Automation* – pertaining to the increased use of automation for normal and safety operations and its application beyond process control to all aspects of plant operations
- *Interfaces to Automation* – pertaining to the human-system interfaces used by operators to monitor, configure, interact with and control automation

In 2012, the NRC published a study outlining the human-performance issues related to the design and operation of SMRs (O'Hara, Higgins & Pena, 2012). Two automation-related issues were identified. One issue, "High Levels of Automation for All Operations and its Implementation," similarly concluded the levels of automation issue identified in the earlier study. The second issue, "Function Allocation Methodology to Support Automation Decisions," addressed the fact that function allocation methodologies have not kept pace with automation technology, thus there is a need for improvements in the methods available to designers for making automation decisions.

Human-automation interaction was also identified in the NRC's report to Congress (NRC, 2012) on advanced reactor licensing and identified research needed to support licensing:

> The future designs will generally rely on passive rather than active safety features and may involve concurrent control of multiple modules from a common control room. In general, these designs will employ digital I&C [instrumentation and control] technology as opposed to the predominantly analog I&C technology used in the current fleet of operating nuclear plants. These systems will provide the capability for increased automation that makes greater use of interactions between personnel and automatic functions. Automation can change the operators' role in monitoring, detection, and analysis of off-normal conditions, situation assessment, and response planning. Research is needed to determine the effect of these changes on operator safety performance and on plant safety.

Therefore, the nuclear industry, from both the designer and regulatory perspectives, have identified issues related to human-automation interaction as significant in the development of future commercial NPPs.

As a new generation of NPPs emerge and existing plants are modernized with advanced I&C and automation technology, it is imperative that the design of automation is based on sound scientific and engineering principles that support human-automation collaboration, efficient performance, and safety. Despite its importance, there is very little HFE guidance available to designers to support the implementation of these technologies or to regulator reviewers who must evaluate their safety.

1.3.2 Automation Support for Tasks Involving Specific Human-System Interfaces (HSIs)

Operators engage in generic tasks, such as monitoring and situation assessment, to accomplish plant safety and production goals. Operators perform these tasks with the aid of the HSIs in the control room and in other operations locations in the plant. Through the alarms, displays, computerized operator support systems (COSSs), procedures, and controls, HSIs provide information about the plant in order for operators to take actions to start, control, and stop plant systems and equipment (see Figure 1-1). The NRC conducted several studies examining the automation support for specific tasks and the HSIs used to perform them (e.g., the use of computer-based procedures for performance of response planning and procedure management tasks (O'Hara, Higgins, Stuble & Kramer, 2000) and the use of advanced alarm systems for monitoring and detection tasks (O'Hara, Brown, Higgins & Stubler, 1994). These studies developed guidance for the review of these specific HSIs which were integrated into NUREG-0700 (O'Hara & Fleger, 2020).

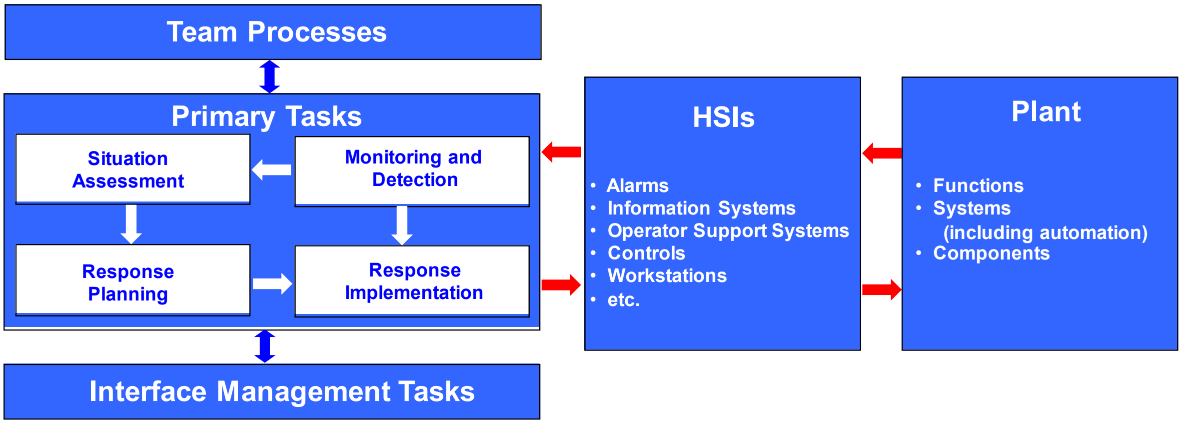

Figure 1-1 Operator task performance using HSIs

In 1994, the NRC published a study examining potential improvements to plant alarm systems. In most complex human-machine systems like NPPs, the operator's monitoring and detection tasks can easily be overwhelmed due to the large number of individual parameters and conditions involved (O'Hara, Brown, Higgins, & Stubler, 1994). Therefore, support is generally provided for these activities by an alarm system. The alarm system is one of the primary means by which abnormalities and failures come to the attention of the personnel. An "alarm system" is essentially an automated monitoring/detection system.

One of the major challenges facing NPP operators is the sheer volume of alarms that come into the control room following a plant transient. While some improvements were put into effect following the Three-Mile Island accident, they did not do enough to address the alarm avalanche problem. A primary focus of the O'Hara et al., 1994 research was on alarm processing techniques. Generally, these are techniques that process "raw" alarm information to determine if new alarm information is valid and presents new information to operators. Two general classes of alarm processing techniques were discussed: (1) signal processing and (2) condition processing. When instrumentation failures occur, such as a failed sensor, biased or false signals are generated. The use of these signals by the alarm system may result in the presentation of either false or nuisance alarm messages. Such alarm messages are misleading and may interfere with the operator's situation assessment or reduce the crew's confidence in future alarm messages. Signal validation is a set of techniques by which signals from redundant or functionally related sensors are automatically evaluated to determine whether a true alarm condition exists. An example is to analyze normal signal drift and noise signals to eliminate those that momentarily exceed the setpoint limits but are not indicative of a true alarm condition. Alarm conditions that are not eliminated by the alarm signal processing may be evaluated further by alarm condition processing. Thus, spurious alarms are not presented to operators.

Alarm condition processing refers to the rules or algorithms that are used to determine the operational importance and relevance of alarm conditions. This is done to determine whether the alarm messages that are associated with these conditions should be presented to the operator. Four classes of processing techniques were defined: (1) nuisance alarm processing, (2) redundant alarm processing, (3) significance processing, and (4) alarm generation processing. Each processing technique changes the resulting information provided to operators. The research into alarm processing techniques represents an application of automation to the evaluation of individual alarms much as an operator might cognitively do if such a capability were not available.

In 1994, the NRC also developed some general guidance for COSSs that were typically operator aids that supported situation analysis and decision-making (O'Hara, 1994). COSSs are "knowledge-based" aids that provide assessments of plant conditions and typically do not involve controls. An example of a COSSs is a decision aid for NPP operators that identifies severe accidents and makes mitigation response recommendations (Hur et al., 2015). The guidance addressed the functional requirements of such systems, such as explanation and simulation features, and the desirable characteristics of their user interfaces. The review guidance was derived mainly from existing HFE guidance from the U.S. Department of Defense (DOD, 1990).

Another study focused on automation as applied to plant procedure use and its management (O'Hara, Higgins, Stubler, & Kramer, 2000). Plant procedures are instructions to guide operators in monitoring, decision making, and controlling NPPs. While plant procedures historically have been paper-based, computer-based procedures (CBPs) were being developed to support procedure use. One of the key outcomes of this study was the application of a "levels of automation" concept to individual procedure functions. Table 1-2 illustrates this concept. The table identifies the procedure functions in the first column, organized by the primary generic tasks. The remaining columns show that the function can be performed by operators alone (manual), performed by automation and provided as suggestions to operators (advisory), performed by both operators and automation (shared), or by automation alone (automatic).

Table 1-2 Levels of Automation of Procedure Functions

Procedure Functions	**Level of Automation**[1]			
	Manual	*Advisory*	*Shared*	*Automatic*
Monitoring and Detection				
Process parameter values				
Operator actions				
Situation Assessment				
Procedure entry conditions				
Resolution of procedure step logic				
Step status (incomplete or completed)				
Procedure history				
Context sensitive step presentation				
Assessment of continuous, time, and parameter steps				
Assessment of cautions				
High-level goal attainment and procedure exit conditions				
Response Planning				
Selection of next step or procedure				
Procedure modification based on current situation				
Response Implementation				
Transition from one step to the next				
Transition to other procedures				
Control of plant equipment				

Note: Source is NUREG/CR- 6634 (O'Hara, Higgins, Stubler, & Kramer, 2000), Table 4-1

1.3.3 General Human-Automation Interaction

The NRC studies described above focused on specific tasks and HSIs rather than automation systems in general. Therefore, no general characterization of automation defining the important dimensions of automation that impact operator performance were developed. The studies also did not lead to general review guidance applicable to any human-automation interaction and supporting HSIs.

The first major study to address general human-automation interaction was published in 2010 (O’Hara & Higgins, 2010). The purpose of the study was to develop guidance for the general aspects of human-automation interaction that is applicable to the review of any automated system. The methodology is depicted in Figure 1-2.

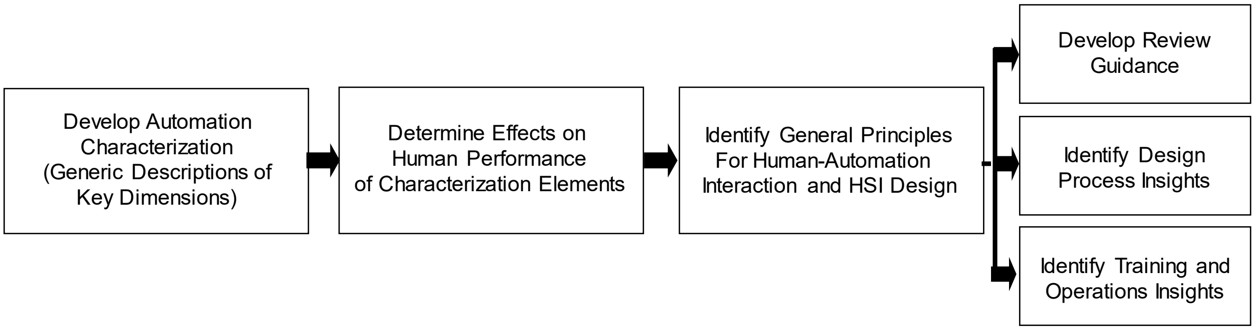

Figure 1-2 Automation review guidance development methodology

A characterization of plant automation that describes the design aspects of automation systems that are important to human performance was first developed. Existing or planned automated systems for several new plant designs, as well as systems outside the nuclear industry were reviewed. Six dimensions of automation were defined: adaptability, generic tasks, levels, processes, modes, and reliability. Each dimension is described below.

Adaptability

A system can be designed such that the human or automation agent responsible for performing an activity is always the same (i.e., static allocation). Alternatively, the allocation can change dynamically based on situational considerations, such as the operator's overall workload. This is adaptive automation (AA), and the factors that cause changes in allocation are called "triggering conditions."

Generic Tasks

Generic tasks refer to the cognitive functions where automation has been applied. The classification that has been used is the basis for many NRC HFE guidance efforts (O'Hara et al., 2008a). It includes the following functions:

- monitoring and detection - are activities involved in extracting information from the environment to check the state of the plant and determine whether it is operating correctly
- situation assessment - is evaluating current conditions to assure their acceptability or determining the underlying causes of any abnormalities
- response planning - is deciding upon a course of action to address the plant's current situation
- response implementation - is undertaking the actions specified by response planning
- interface management - pertains to activities such as navigating or accessing information at workstations and arranging various pieces of information on the screen

Levels

The level of automation (LOA) is the degree to which an activity is automated, extending from manual (i.e., performed by personnel without automation) to fully automated (i.e., performed with little to no personnel involvement). Many taxonomies have been defined, and fitting NPP automation applications to a levels-of-control framework were sought. Five levels were designated (see Table 1-3).

Table 1-3 Levels of Automation for NPP Applications

Level	Automation Functions	Human Functions
1. Manual Operation	No automation	Operators manually perform all functions and tasks
2. Shared Operation	Automatic performance of some functions or tasks	Manual performance of some functions/tasks
3. Operation by Consent	Automatic performance when directed by operators to do so, under close monitoring and supervision	Operators monitor closely, approve actions, and may intervene to provide supervisory commands that automation follows
4. Operation by Exception	Essentially autonomous operation unless specific situations or circumstances are encountered	Operators must approve of critical decisions and may intervene
5. Autonomous Operation	Fully autonomous operation. System or function cannot normally be disabled, but may be started manually	Operators monitor performance and perform backup if necessary, feasible, and permitted

Processes

Automation uses input from the plant (and perhaps the operator) and processes the information to accomplish a goal. These processes are an important aspect of automation in that they are the means by which automation performs its tasks. Automation processes can include control algorithms, decision logic[6], and virtually any other type of information processing routine suited to its tasks.

Modes

Automated systems may have different modes of operation. Modes define sets of mutually exclusive behaviors that describe the relationship between input to the automation and the response to it (Jamieson & Vicente, 2005). A system can have multiple modes, but only one is active at a time. Modes do not imply differing levels of automation; rather, they involve performing the same function in different ways. Modes are beneficial in providing the capacity for a system to do different tasks, or to accomplish the same task using different strategies under changing conditions.

Reliability

All engineered systems have less than perfect reliability. Automatic systems can fail in whole or in part and thus compromise their ability to achieve their intended function. When an automatic system has a simple, well-defined task to accomplish, its reliability is easy to quantify (e.g., as the probability the system will correctly perform its function). When its functions and tasks are complex, as is the case for many COSSs, defining the measures of reliability is more difficult. Further, it may be important to distinguish different aspects of an automatic system's functions. Therefore, for an alarm system, reliability can be expressed in terms of misses (not alarming when alarm conditions exist) and false positives (alarming when an alarm condition does not

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[6] An example is the use of Boolean logic.

exist). Further, automation's reliability may differ across different contexts of use, or modes of operation.

This is a generic characterization of automation that defines the design envelope wherein any specific application of automation can be designed. That is, any automation system will be applied to specific generic tasks, using a specific LOA, using either static or dynamic adaptability, with specific process and modes, at a specific level of reliability.

These dimensions are important because, in addition to identifying adaptability as a dimension that describes that aspect of automation design pertaining to AA, the others are important to the understanding of how automation can change to provide adaptive support.

To determine the effects of automation's dimensions on performance, dimensions of performance are needed as well. Performance can be characterized into three broad categories. The first is *integrated system performance* that includes measures such as mission/function performance and process task performance. The next category is *cognitive task performance*, with measures such as situation awareness and workload. Finally, the last category is *teamwork*, which includes measures such as trust, communication, and coordination.

Reviews of operating experience and evaluations of relevant literature in HFE, automation, and control, to develop models of the effects of the automation's dimensions on performance were conducted. In the early stages of research such models are descriptive. When sufficient information is obtained the models can become mathematical to quantify the relationships.

For example, Figure 1-3 depicts a model relating the relationship between automation's reliability and the operator's trust. When the operator's perceptions accurately match the automation's reliability, trust is "well-calibrated" and operators use it appropriately. When the operator's trust does not match automation's reliability, the "miscalibrated" trust leads to problems in how operators use automation. When operator trust is high despite low automation reliability, automation is misused (i.e., continues to be used when it should be abandoned). When operator trust is low despite high automation reliability, operators inappropriately stop using automation (disuse) when they should not.

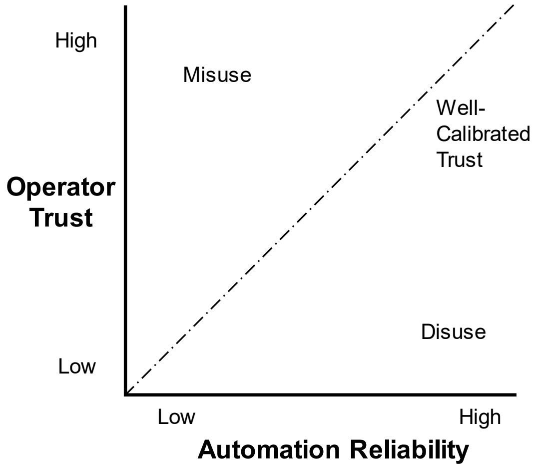

Figure 1-3 Effect of automation's reliability on operator trust and use of automation

Another example is illustrated in Figure 1-4. This figure shows that operators are sensitive to the variations in automation's reliability (although their perceived reliability is not necessarily accurate). As automation becomes less reliable, task performance declines to a point where automation is abandoned. Task performance can rebound a little as the operator shifts cognitive resources from dealing with the automation back to performing the task.

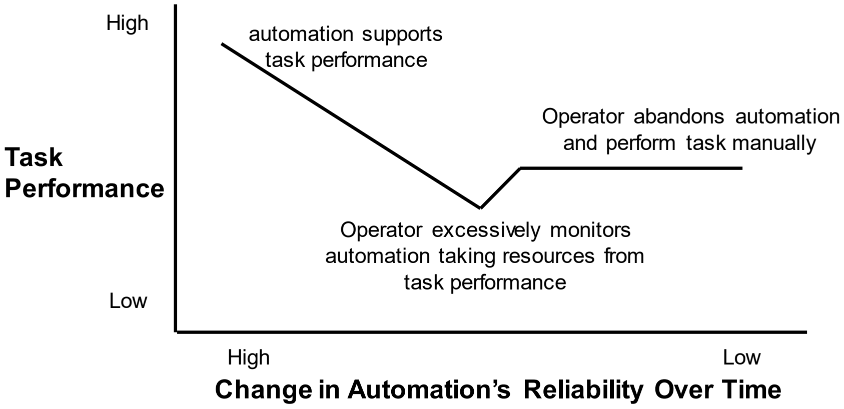

Figure 1-4 Effect of automation's reliability on task performance

The research for each of the six automation dimensions to model its relationship to performance were reviewed. This information formed a technical basis that was used to develop design review guidance for human-automation interactions (O'Hara & Higgins, 2010). The guidance was updated and revised prior to its integration into NUREG-0700, Revision 3 and is discussed in Section 7.2 of this report.

In addition to guidance development, the research identified several emerging issues, one of which was AA. As noted above, the automation dimension of adaptability encompasses AA. AA is viewed as a potential means of improving the human-automation interaction and providing a means to mitigate some of the human performance issues associated with highly automated systems (Table 1-1). The purpose of the current study is to look specifically at AA and define the state-of-the-art in AA research and application in operational systems in general as well as those in the commercial nuclear industry.

1.4 Organization of This Report

Section 2 describes the study's objectives and methodology. In Section 3, a definition and characterization of AA are provided, and the potential benefits of AA are discussed. In Section 4, AA applications in the commercial nuclear industry are identified.

Section 5 presents the results of the research on the effects of AA on performance, including both normal operations and the management of degraded conditions. Human-automation interaction is discussed in Section 6. Topics include the modeling of human-automation interaction and teamwork, the design of HSIs to support that interaction, and the application of adaptive approaches to the design of the HSIs themselves.

In Section 7, the HFE guidance available for designing and evaluating AA systems were reviewed. The guidance addresses function allocation, the detailed design of AA, and its evaluation and validation.

The results are discussed in Section 8. The lessons learned from this research are summarized and approaches to improving human-automation Interaction are recommended. Potential applications of AA in commercial nuclear plants were also examined. Finally, research and development needs are presented along with final conclusions.

2 OBJECTIVES AND METHODOLOGY

The need for guidance related to human-automation interaction has been made in the general HFE literature (Sebok et al., 2009 & 2010) and for NPP design in particular (Dudenhoeffer et al., 2007). The need for such guidance to support NPP reviews was recognized by NRC RES (O'Hara et al., 2008a; O'Hara & Higgins, 2010; O'Hara, Higgins, & Pena, 2012); an NRC User Need (NRC-NRO, 2012); and NRC report to Congress (NRC, 2012). Research on adaptive automation is an extension of this need for improved guidance on automation in general. In addition, this research was specifically requested by the Office of New Reactors (now the Office of Nuclear Reactor Regulation). The methodology used to provide an improved technical basis for human-AA interaction is described in this section.

2.1 Objectives

The objective of this research is to perform a scoping study to extend the NRC's understanding of the application of AA to NPP operations by developing a characterization of AA systems and a technical basis consisting of current research and experience with them. As a scoping study, the aim is to develop an AA characterization and a technical basis that can serve as the foundation for review guidance, which if needed, can be developed as part of a future project. Specifically, the research will address the following topics:

- applications for AA in operating systems, including NPPs
- performance benefits and safety implications of AA applications
- triggering conditions used and their relative advantages and disadvantages
- measures of system, operator, and crew performance that are needed to implement AA for the identified potential applications and the associated challenges with obtaining and using such measures
- HSI design considerations for implementing AA (e.g., communicating and negotiating re-allocation of functions)
- challenges AA applications present to the NRC's existing regulatory review framework/processes

2.2 Methodology

In this section, a brief overview of the methodological steps undertaken are provided. Figure 2-1 is an overview of the main steps in the project's methodology.

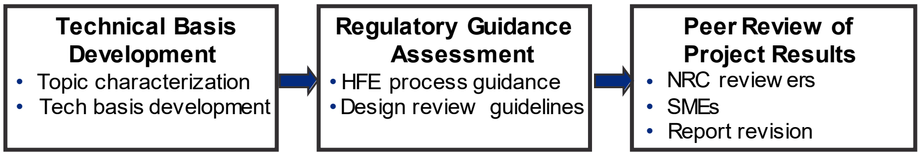

Figure 2-1 Major steps in the project's methodology

Technical Basis and Guidance Development

Guidance development involves several steps including: topic characterization, technical basis development, and guidance development and documentation.

Topic Characterization
To develop a technical basis, a characterization of AA needs to be developed. The characterization describes the design aspects of AA systems that are important to performance. The characterization must be sufficiently robust to accommodate the review of a diversity of systems that designers may employ. Characterization is important because it affords a structure for developing and organizing review guidance. Also, it gives the reviewer a framework for performing the design safety reviews. To develop the characterization, existing AA systems from both the general literature as well as the nuclear industry were reviewed. The AA characterization is discussed in Section 3 of this report.

Technical Basis Development
Once the characterization was completed, research to determine the effects of AA on human and integrated system performance was conducted. The research was used to identify issues and best practices for supporting performance. Information from a variety of sources was used (see Figure 2-2).

Existing HFE standards and guidance documents were reviewed. However, little guidance is provided for the design of for AA in most HFE standards and guidelines. There are a few exceptions (e.g., the Federal Aviation Administration's *Human Factors Design Standard* (HFDS) (Ahlstrom et al., 2003)), and these standards and guidelines are discussed in Section 7.

Chapters in HFE handbooks offering sound analyses and syntheses of existing literature (e.g., Cong, 2009) were sought. Such documents are invaluable in that they constitute a review of research and operational literature by knowledgeable experts. Literature, consisting of papers from research journals (e.g., Miller & Parasuraman, 2007) and technical conferences (e.g., Calhoun, Ward & Ruff, 2011) describing work in the nuclear as well as other industrial domains were reviewed and formed the bulk of the technical basis.

Nuclear industry experience also was obtained from interviews and communications with vendors, researchers, and consultants with knowledge of NPP automation and a site visit to an NPP design organization.

The information to identify consistent findings and lessons learned were reviewed. These reviews, findings, and lessons learned formed the technical basis of information on AA. The results of this effort are described in Sections 4 through 7.

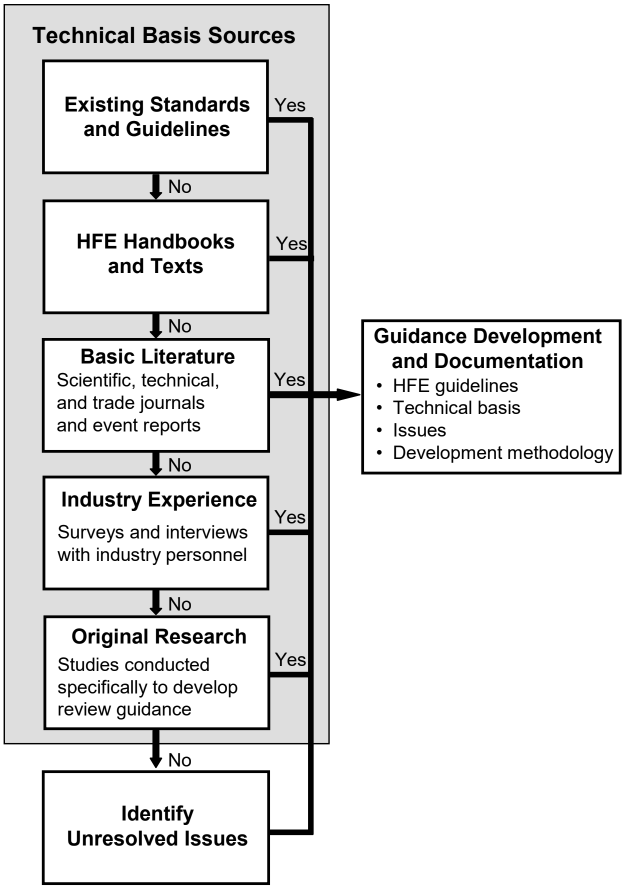

Figure 2-2 Technical basis and guidance development

When a technical basis for a topic is developed, typically additional research issues are identified as well. These are aspects of the topic for which insufficient information is available in the literature to derive clear findings and lessons learned. Several research issues for AA were identified and summarized in Section 8 of this report.

Regulatory Guidance Assessment

Once the technical basis is established, the results will be considered with respect to the challenges AA applications may present to the NRC's existing regulatory framework/processes. The main focus of this evaluation will be the detailed guidance in NUREG's 0700 and 0711. However, other NRC review guidance will be assessed as well. The results of this assessment are published in a separate report (O'Hara, 2017).

3 CHARACTERIZATION OF ADAPTIVE AUTOMATION

3.1 Defining Adaptive Automation (AA)

AA is referred to in slightly different ways in the literature. Some common terms include: adaptable automation, adaptive systems, collaborative automation, adjustable autonomy, dynamic task allocation, dynamic function allocation, cooperative control, mixed-initiative systems, and adaptive aiding. Some of these terms encompass more than AA exclusively.

This section defines AA and how it differs from other types of automation. Several definitions of AA can be found in the literature:

- "the dynamic, real-time allocation of tasks to the operator or automated system in a flexible manner in order to improve system and operator performance and to minimize performance degradations" (Arciszewski et al., 2009)
- "the real time allocation of tasks to the user or automated system in a flexible manner, changing the automation to meet current situational demands" (Ahlstrom et al., 2003)
- "the technological component of joint human–machine systems that can change their behavior to meet the changing needs of their users, often without explicit instructions from their users" (Feigh et al., 2012)

These definitions capture two key characteristics of AA that make it different from other types of automation. First, AA is characterized by F/Ts that are allocated *dynamically*, rather than *statically*. Typically, allocations are statically defined as part of the design process. For example, designers decide what LOA is best for a particular automatic system. Once designed, it functions in that manner and the LOA does not change. By contrast, AA systems are designed to be flexible such as to offer different degrees of automation. As a result, AA systems have more than one configuration, where a configuration is a defined set of responsibilities for automation and the human crew.

The second key characteristic of AA is that the dynamic changes in allocation are triggered based on changes to current situations (e.g., changing events, plant conditions, or operator states). This reflects a goal of AA, to provide just the right amount of automation at all times (i.e., less when operator workload is low and more when operator workload is high). By providing just the right amount of automation, the goal of AA designers is to optimize overall system and operator performance and minimize some of the negative aspects of highly automated system.

With these two key characteristics in mind, AA is defined as the dynamic, real-time change in the degree of automation (DOA) in response to situational changes:

- DOA changes (i.e., changes in automation's configurations) can include adaptions such as increasing or decreasing the LOA and the reallocation of specific tasks to/from operators and automated systems
- situational changes (i.e., triggering conditions) include changing events, plant conditions, or operator functional states

A more detailed discussion of automation configurations and triggers is contained in Section 3.3 below.

3.2 Potential Benefits of Adaptive Automation

There are reasons why operators may want higher or lower levels of automation at different times. Operators may wish to have more automation when the pace of the task/event makes it difficult to proceed in a step-by-step manner and increasing the DOA can help speed overall progress. Operators may also want to increase automation when they need to perform other F/Ts. AA systems provide the opportunity to delegate ongoing F/Ts to the automation thereby freeing operators to focus on other F/Ts.

Operators may want to lower the levels of automation and involve themselves more directly in overall F/T performance. This is desirable when the situational context is important to interpreting task steps. For example, operators may know that a particular piece of equipment is about to become available due to maintenance activities while such information may not be available to the automation. More generally, operators may wish to lower automation levels to ensure high SA of task details and increase workload during periods of low workload where boredom and complacency are concerns. Finally, operators may want to lower the levels of automation in order to maintain manual task skills.

AA may benefit users by enabling them to remain in active control of the system instead of becoming passive observers. Specific benefits are expected to include the following (Bindewald, et al., 2014; Parasuraman & Wickens, 2008):

- *Improved task performance* – improve F/T performance by increasing the DOA when manual performance is not at acceptable levels
- *Improved SA* - keeping operators in the loop and vigilant or increasing operator responsibilities if SA is low. Farrell and Lewandowsky (2000) suggest that improved operator knowledge and memory for automation's behavior may result from intermittent adaptive reallocation of responsibilities.
- *Improved workload management* – workload can be maintained at acceptable levels (not too high, low, or variable)
- *Improved manag*ement *of automation failures and degraded conditions* – improved detection of automation failure and management of recovery, including the maintenance of the skills needed to perform tasks

3.3 Key Dimensions

Earlier, AA was defined as the dynamic, real-time change in the DOA in response to situational changes. These two characteristics are linked to two key design aspects of AA: configurations and triggering conditions. Configurations describe how the relative role and responsibilities of humans and automation change as F/Ts are dynamically allocated. Triggering conditions describe the initiators that cause changes in configurations in response to situational changes. A third key design aspect of AA is the HSIs crews use to monitor, configure, and interact with AA systems and functions.

The description of key AA design characteristics presented in this section reflect both the definition of AA and the identification of an important dimension that emerged from the research discussed in sections that follow. The characterization at this point is presented because it provides a standardized means to discuss various aspects of AA that are not always defined consistently in the literature.

3.3.1 Configurations

A configuration is a DOA that defines the roles and responsibilities of both operators and automation. As stated above, AA configurations are often described in terms of changes in the LOA (e.g., as operator workload rises, the LOA increases). However, configuration changes can be more complex and involve other automation dimensions, such as the generic tasks that are automated (Pararuraman, Barnes, & Cosenzo, 2007). Feigh et al., (2012) identified four different types of configuration changes, which the authors called "adaptations:"

- *Function allocation* – a change in who performs an F/T, human or automation agent (this type encompasses Wickens' DOA)
- *Task scheduling* – a change in when tasks are performed, including their duration and priority
- *Interactions* – a change in how the AA interacts with human agents
- *Content* – a change in what information is presented to human agents

These examples illustrate the diverse ways AA configurations can dynamically change.

Wickens used the term DOA to refer to the combination of the LOA and generic task dimensions of automation (Onnasch, Wickens, Li & Manzey, 2014; Wickens, Li, Santamaria, Sebok, & Sarter, 2010)..[7] The higher the LOA and generic task, the higher the DOA. For example, this can include changes in the levels of automation, generic tasks performed by automation, specific tasks performed by automation, the processes automation uses to perform its F/Ts, or the modes of automation.

Since AA configurations can involve changes in individual automation dimensions, which have separate effects on human performance, lessons learned about each should guide the design of the configurations.

Thus, configurations reflect changes in the relative roles of human and automation agents. There are several design considerations when implementing AA configurations:

1. Configuration Definition - Should the configurations be predefined or defined in real time?

2. DOA Change Selection - What type of DOA changes should be used to support operator task performance?

3. Number of Configurations - How many individual configurations should be designed?

4. Configuration Timing - What is the minimum length of time configurations should remain in effect?

First, should the configurations be predefined or defined in real time? That is, should they be defined by designers and built into the AA system or should operators be given the flexibility to define role changes in real time. There is a tradeoff between these options (i.e., when predefined, operator and automation roles can be clearly defined, and when operators can be trained for each configuration). Further, the DOA configuration options can be designed into the HSI so they can be easily changed. However, the configurations will be somewhat general and

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[7] Note that generic tasks are called "stages of automation" in Wickens' framework.

may not be exactly tailored to the current situation. Providing operators the flexibility to define changes in real time would enable such precise tailoring. However, the workload to do so might be high and training on the changes in operator responsibilities would not address every possible configuration change.

The second consideration is the type of DOA changes that should be used to support operator task performance. The DOA can change along different automation dimensions, such as the LOA and the tasks performed by automation. An example of the former is authorizing automation to take action without operator approval when workload increases.

The third consideration is how many configurations are available. Can too many configurations lead to potential issues, such as those identified in studies of flight management systems where it becomes difficult for operators to keep track of the different modes of operations and the relative responsibilities when each is in effect (Flight Deck Automation Working Group, 2013)? Mode transition research has shown that (Mosier et al., 2013):

- operators do not monitor automation’s mode transitions well
- operators often do not know a mode change has taken place
- systems with multiple modes are particularly problematic and increase the probability of automation-related errors

The fourth consideration is the length of time a specific configuration remains in effect. Configurations are operative for a period of time and stay in effect until another trigger either changes the configuration or terminates the automation. The question arises as to how long configurations should remain in effect. It is likely that too many rapid changes will be confusing and lead to difficulty keeping track of the relative responsibilities of all agents. Configurations should be long enough to not be confusing to operators.

3.3.2 Triggering Conditions

Triggers are the conditions that initiate changes in AA configurations. Note, there is a distinction that is sometimes made between configuration changes requested by the operator and changes made by the system without operator request. Some authors refer to the former as “adaptable” automation and the latter as “adaptive” automation (e.g., Kidwell et al., 2012). The term “adaptive” is simply used and consider human control of AA configuration changes as one type of trigger. This is consistent with most of the literature (Feigh et al., 2012).

There is a tradeoff between operator-requested configuration changes and non-operator requested triggers (Kaber, 2012). Operator initiated triggers increase workload because operators must take an action for a change to take place. This workload increase may come at a time when operators want to initiate automation because their workload is already high, thus the requested change only serves to further increase workload. As prior research has shown, operators sometime decide not to take such actions as part of their overall workload management strategy (O’Hara & Brown, 2002). Therefore, when operator-requested triggers are used, designers should seek to minimize the workload associated with it. The cognitive cost of initiating automation cannot outweigh its benefits or operator will not use it (Parasuraman et al., 2009).

Non-operator requested triggers do not impose additional operator workload. However, operators may become disoriented or distracted by the initiation of automation change. This disorientation may cause transient performance decrements. When non-operator requested triggers are used, designers should seek to design strategies to alert operators to the change in a manner that minimizes distractions and interruptions.

Feigh et al., (2012) identified five categories of triggers:

- *operator-based triggers* – changes in AA configuration can be made based on the operator directly or by a system assessment of the operator state
- *system-based triggers* – changes in AA configuration can be made based on current or predicted system states
- *environment-based triggers* – changes in AA configuration can be made based on states of the environment or events external to the system and its operators
- *task- and mission-based triggers* – changes in AA configuration can be made based on mission goals and tasks
- *spatiotemporal triggers* – changes in AA configuration can be made based on time and location

Focusing on non-operator requested configuration changes, Parasuraman et al., (1992) and Yoo (2012) identified five main categories of techniques:

- *critical events* – events that will change demands on operators, such as an emergency operating procedure initiator
- *operator performance measurement* – measuring operator task performance
- *operator physiological assessment* – measuring physiological parameters to assess conditions such as high workload
- *operator modeling* – models of operators that “incorporate rule bases on operator resources, strategies and intentions”
- *hybrid methods* – combining one or more of the above

Parasurman’s trigger categories focus on changes to the operator. Since there are relative benefits and disadvantages to each type of techniques, the use of hybrid methods helps to ensure that automation is initiated (or changed) when it should be (Parasuraman et al., 1992; Sheridan & Parasuraman, 2005). Parasuraman et al., contend that hybrid triggers may lead to a more robust, resilient system that is less subject to potential problems or errors of individual triggers.

For the purposes of this report, the following categories of triggers appropriate to potential NPP applications of AA were identified:

- *operator commanded* – a configuration change is made when commanded by the operator. Plant start-ups and mode changes are typically performed in this manner
- *operator functional state* – a configuration change is made when an operator state threshold is reached (e.g., high workload level, low SA, and fatigue). This class of triggers requires monitoring of operator state (e.g., using physiological measures).
- *operator performance* – a configuration change is made based on a change in operator task performance, such as when an operator fails to perform a task or when performance falls below a threshold for acceptability
- *system state* – a configuration change is made when a system state change is detected or needed based on the current configuration (encompasses Feigh’s mission triggers)
- *event based* – a configuration change is made when specific situations are detected (encompasses Feigh’s “spatiotemporal” and “environment-based” triggers)

- *hybrid* – more than one class of the above triggers is used, such as when a configuration change is made when specific situations are detected

Parasuraman et al., included a category of modelling techniques. Such techniques can contribute to the development of triggers for operator state, operator performance, or system state. Therefore, a separate category for those were not included.

In addition to operator commanded triggers, the primary focus is on triggers that relate to task performance and operator functional states (i.e., operator conditions such as high workload level, low SA or fatigue) that may impact their ability to accomplish their roles and responsibilities, and perform their tasks. The other triggers, such as changes in plant conditions or events, can be surrogates for changes in operator functional states. For example, a change in plant state may be expected to alter operator workload and, therefore, give rise to a situation where increased automation is warranted. A change in automation made in response to the presence of a compromised functional state can be requested by the operator or made by the system upon detection of a triggering condition.

There is an advantage when automation can be triggered both by operators and the system itself. This is referred to as "co-agency" (Inagaki & Sheridan, 2012). Even when operators have accurate SA, it does not necessarily mean that an unwanted situation can be avoided. Operators may not have sufficient time to respond, may fail to take the response, or may give an improper response. In such situations, it is reasonable to authorize automation to respond if it can detect the operator's failure to respond appropriately.

Inagaki and Sheridan (2012) identified two types of errors that can be detected by automation. In an alpha error, an operator response is needed, but not taken. In a beta error, automation detects an inappropriate response to a situation. These possible situations are illustrated in Table 3-1. With respect to automation's monitoring of operator behavior, automation can respond by providing a warning about the impending error or it can provide support for the action. In the latter situation, the potential error can act as a triggering condition for automation to respond, if the operator fails to respond to the warning.

Table 3-1 Automation Monitoring of Operator Action

	Operator Response	
Automation Judgment	Response appropriate	Response not appropriate
Response detected	correct response	beta error
Response not detected	alpha error	correct non-response

Note: Table adapted from Inagaki and Sheridan (2012)

Designers need to assess how automation should respond and whether it is appropriate for automation to take an action or prevent an operator action based on the specific system and the consequences of each type of error. Inagaki and Sheridan (2012) suggested that operators can accept machine-initiated trading of authority if automation is addressing what they are unable to do or fail to do. However, operators may be reluctant to accept the machine-initiated trading of authority if automation is preventing operators from doing what they want to do.

Designers need to assess whether machine initiators are acceptable for a specific application and how automation will respond when they occur, either by warning or by action.

An important consideration in the design of triggers is when the trigger specifically causes a shift in AA's configuration (i.e., a shift in the DOA). This is referred to as the 'invoking threshold" (de Visser & Parasuraman, 2011; Rusnock & Geiger, 2013). To illustrate the issues, consider an adaptive system using task performance as a trigger. The configuration is changed based upon predefined performance setpoints. If performance is drifting above and below this setpoint every few seconds, the automation configuration would be shifting every few seconds. This could be very distracting to the operator and disruptive to performance. The issue can be even more significant with physiological measures. Human physiological parameters can rise and lower rapidly which, if they cross the setpoints established to trigger configuration changes, can lead to rapid changes in the DOA. Methodologies to use measures associated with triggering conditions to set appropriate invoking thresholds is an important consideration in the design and the review of AA systems.

There are two decisions that are important to the design of triggers:

1. Appropriateness of Trigger Categories - Which category of trigger or combination of categories is appropriate for the specific AA system?

2. Invoking Thresholds - When should the trigger cause a shift in AA's configuration, the "invoking threshold?"

To summarize, AA is characterized by different automation configurations that change the DOA based upon triggering conditions. Individual configurations may be in effect for varying lengths of time and changed when the invoking thresholds associated with triggering conditions are reached or when automation is terminated. Triggering conditions can be defined based on a wide range of factors from operator request, to operator functional state, to plant state, to detection of key events. Figure 3-1 illustrates the relationship between configurations and triggers.

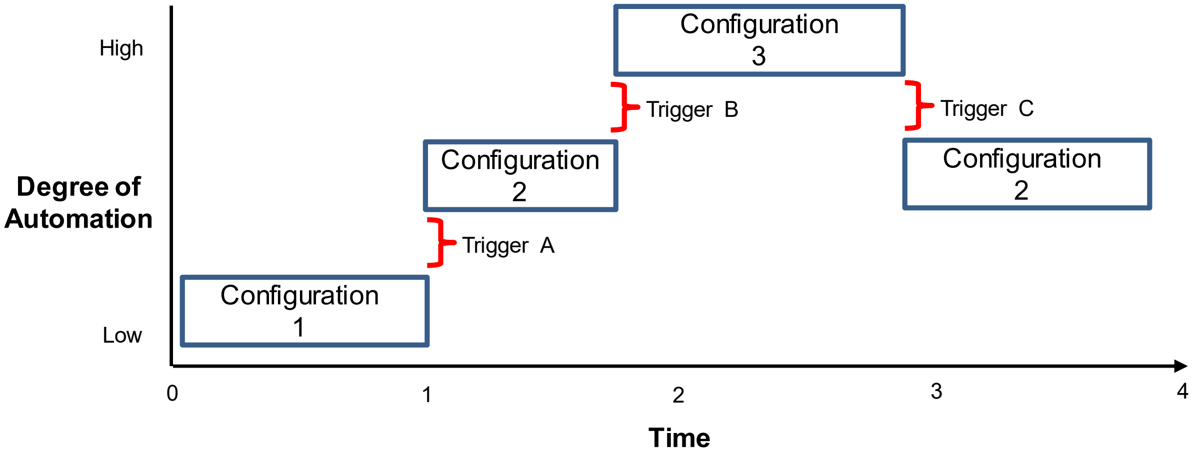

Figure 3-1 Dynamic changes in automation over time

3.3.3 HSIs

HSIs provide the link between operators and automation. HSIs are made up of the alarms, displays, controls, and interaction functions used by operators to monitor, control, and communicate with AA systems and functions.

Monitoring is a key task plant operators perform using control room HSIs. They monitor overall plant performance as well as systems and subsystems supporting that performance. A long-standing issue operators have in highly automated system is the monitoring of automation. One factor contributing to this issue is poorly designed HSIs (O'Hara & Higgins, 2010). With respect to AA, monitoring may be more significant because the roles and responsibilities of both operators and automation will change, unlike the case with static automation. Ensuring operator awareness of the current configuration and when configuration shifts are triggered are key considerations in the design of HSIs for AA systems.

An important consequence of monitoring is that operators may be less likely to be aware of automation degradations and failures. HSIs provide alerts, alarms, and displays to support monitoring but how well HSIs support SA and the detection of degraded conditions is a significant consideration in the review of an AA system.

HSIs also provide controls for all operator interactions with automation (e.g., to configure automation and control what it does). AA has some unique control considerations:

- change AA's current configuration (an operator-commanded trigger)
- override a configuration change triggered by a non-operator commanded trigger
- interactions with functions provided by delegation-type interfaces
- some AA system may also have controls to modify configurations in real time

Operator interaction with automation can also impose on workload. A key consideration is how this workload is managed. If automation control is simple and imposes minimum workload, operators are likely to use it effectively. If the control of automation is cumbersome and imposes high workload, operators may refrain from interacting with it to manage overall workload.

AA systems are likely to be more interactive with operators compared to static automation and can be viewed a part of a multi-agent system. Despite the absence of a comprehensive teamwork model to guide the design of how automation agents interact with their human teammates, a key consideration for any team is communication. Communications should be timely with respect to the importance of the information and not distracting and disruptive to the crew's ongoing task performance. The designer's challenge is to design communication to ensure that it is effective, yet minimally disruptive given the importance of the information to be communicated. This issue is not unique to AA systems. AA systems differ from other forms of automation because of the amount of communication that is likely. Since AA systems may dynamically change DOA configurations in real-time, it can be expected that they will require more communication between human and automation agents.

The general concerns with designing user interfaces to automation relate to some of the classic human-automation interaction concerns such as loss of SA and increased workload. AA can exacerbate these concerns because of its potential for an increased need for interaction and a loss of awareness about what AA is doing and what the current agent roles and responsibilities are as AA configurations change. Workload is an important consideration because operators may fail to use automation properly if too much effort is required to do so.

There are several decisions that are important to the design of HSIs that have potential consequences for human performance; hence they should be addressed in an HFE safety review:

1. Monitoring - How is SA and the detection of degraded conditions supported?

2. Control - How do operators configure and control automation and how is workload managed?

3. Communication - How is communication between operators and automation fostered?

4 APPLICATIONS OF AA IN COMMERCIAL NUCLEAR PLANTS

While the commercial nuclear industry has developed some AA design applications, there has been very little research on AA. New plant designs are more highly automated than most currently operating plants in the U.S. O'Hara and Higgins (2010) reviewed the levels of automation employed in new designs. While different levels of automation are used, in many cases, operators can override the automation and perform the F/Ts manually. An operator's ability to select between simple automatic and manual operations has been available for a long time in NPP plant designs. This is not considered to be an AA system since the decision to shift between manual and automatic operations is not typically based on operator functional states (OFSs), such as workload. While different static levels of automation have been used in NPP designs, there are few examples of adaptive systems.

General Electric's (GE) Advanced Boiling Water Reactor (ABWR) has an AA system for management of normal plant operations (GE, 2007). The Power Generation Control System (PGCS) provides three levels of automation that are selected by the operators: manual operation, semi-automated operation, and automatic operation. In manual operation, the operator decides what control actions to take and performs the actions with no support from the PGCS. In the semi-automated level of automation, the PCGS monitors plant performance, as well as operator actions, and provides guidance of performing changes on plant status. At this level, the PCGS is advisory and does not perform any control actions. The third level is automatic operation and the PCGS performs control actions. The PGCS cannot change a safety-related system. If a change is to a safety system is needed, the PCGS prompts the operator to perform the change manually. Also, the PCGS goes to manual operations if an abnormal condition or major change in plant status, such as a reactor scram or turbine trip, is detected.

An adaptive approach to operations, called "Functional Integrated Treatments for Novative Ecological Support System" (FITNESS), was developed by Électricité de France (EdF) as a prototype for the next-generation EdF plant (Pirus, 2004a and 2004b). FITNESS was a prototype system run on a plant simulator. One of its foundation principles was that fixed levels of automation are problematic for operators because the operational demands vary, thus it is necessary to provide more flexible approaches. Therefore, FITNESS gave operators control over the levels of automation in real-time. For example, operators were able to select the degree to which operational procedures were automated (i.e., steps could be manually or automatically performed). In general, FITNESS sought to ensure that operators maintained their focus on higher-level goals and objectives and viewed automation as a means to accomplish this. Pirus stated

> "Entrust the operator with management of the goals … and entrust the automatic controls with the tasks where the added value of the operators is not demonstrated" (Pirus, 2002, p. 4-30).

This principle was reflected in the design of the HSIs as well. A hierarchal approach was used where operational goals and the status of major systems were provided at the top level and successive display levels provided operators with increasing levels of detail. At the bottom of the hierarchy, operators could access detailed component-level displays. This approach supported high-level goal monitoring at the top level and the increasing detail in subsequent display levels supported operations and troubleshooting. At each level, operators could access automation and procedures appropriate to that level. Navigation between levels was accomplished with on-screen navigation links. There were no published empirical evaluations of the design.

A site visit to NuScale Power, Inc. to discuss their concept of operations, automation philosophy, and potential applications of AA was conducted in 2016. At the time, the NuScale design had not been completed, therefore the below characterization is based on the best information available at that time.

The NuScale plant is a 50 MWe integral pressurized water reactor. Each unit comprises a reactor and balance-of-plant systems. In its baseline configuration, a NuScale site will consist of up to 12 units in a common reactor pool (Doyle et al., 2016). The pool has greater than 30 days of passive cooling capacity following an extended loss of AC power event. The reactor is cooled via natural circulation (a passive safety feature) to two steam generators located inside the reactor pressure vessel. The passive safety-features prevent fuel damage for postulated accidents. The nuclear steam supply system is fabricated offsite and will be shipped by rail, truck, or barge to the plant site. The NRC approved NuScale's proposal to operate a plant consisting of 1-12 units from a single control room with a minimum crew of six licensed operators.[8]

Function allocation is guided by criteria contained in design documentation. The basis for allocating functions to automation includes considerations such as, the task is repetitive, the task must be performed continuously, and automation of the task will result in clear operational performance benefits. The allocation process is iterative and is further analyzed as part of NuScale's task analysis methodology. At the design stage, SMEs make decisions about the degree of operator involvement in every aspect of operations. The anticipated crew size for operating a 12-unit site requires a high level of automation in order to manage workload.

Operators have overall responsibility for power production and plant safety. The tasks they perform to accomplish these responsibilities include:

- monitoring the performance of structures, systems, components (SSCs)
- operating local and remote SSCs
- commanding automated sequences
- directing subordinate operators to perform activities
- monitoring the performance of sequences and procedures
- interrupting and reprioritizing sequences or procedures
- monitoring and evaluating Technical Specification conditions
- performing surveillance tests
- reviewing trends
- responding to off-normal conditions
- responding to notifications
- establishing plant conditions to support preventative or corrective maintenance
- maneuvering the plant to support load demand
- summoning additional resources to expand capabilities

If a crew encounters a significant operational problem, the general guidance is to place the plant in a safe condition, typically shutdown.

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[8] Publicly available: Agencywide Documents Access and Management System Accession No. ML20023A318

Automation will support most operational tasks. NuScale personnel are very aware of the classic issues operators face in highly automated systems; thus, their approach to automation is to keep operators actively involved. For example, the startup process is divided into several sequences. At the end of each sequence is a checkpoint where operators verify that the sequence was performed correctly, and startup is progressing normally. Once the verification is completed, operators initiate the next sequence of the startup.

Another example is boron concentration control. The automation monitors boron concentration and if it detects the need for dilution or boration, the automation alerts the operator and provides an action recommendation. The operator can accept the recommendation and implement it, modify the action, or reject it.

As these examples illustrate, operational tasks involve a sharing of responsibilities by both operators and automation using a level of automation called “operation by consent” in the automation characterization. Such an approach helps to keep operators aware and involved.

The NuScale design will include automation of interface management tasks, as well. For example, automation selects the correct unit for alarm response actions. This relieves operators from having to retrieve the alarm response procedure and helps to minimize wrong unit errors.

To address the issue of skills loss in highly automated systems, NuScale had planned for operators to periodically perform tasks manually that are normally automated.

NuScale personnel have identified potential applications of AA. For example, on a reactor trip, the tripped unit’s alarm system goes into a “transient alarm response” mode and automatically silences the alarms. This mode lowers alarm response workload and is intended to improve situation awareness by enabling operators to focus on more important alarms. Another application of AA is used when a transient occurs. The large overview display automatically reconfigures the display to present specific information related to the situation (i.e., the specific information displayed varies depending on what caused the trip). This type of AA reduces the workload associated with display retrieval and organization, and minimizes potential errors of selecting the wrong display.

The design team emphasized the importance of giving operators flexibility in how they interact with automation and the HSI design reflects that philosophy. A “process library” display contains all procedures and automation sequences available to operators. From the display, operators can select and initiate the automation sequences they want. Operators can quickly determine which automation sequences are active and their status on a “workbench” display. At a glance, operators can monitor automation at a high-level. This display also gives operators access to more detailed information about the progress of automation sequences. For more complex automation, detailed information is available on a “system automation page.” There are also automation icons for some sequences that provide yet another means for operators to interact with automation.

The HSIs provided for monitoring and interacting with automation also provide the means to detect degrading and failed conditions. For example, when an automation sequence fails, its icon is outlined with a red box, making it easy to detect. The HSI also provides operators with trend displays and alarms to signal degraded conditions. Operators can set special alarms when the automation process is active. NuScale's HSI design provides multiple ways for operators to monitor and interact with automation.

In summary, NuScale's plant design is highly-automated with automation supporting most operations tasks. The design, at the time, included several applications of AA. Levels of automation are being implemented that permit operators and automation to work cooperatively, thus maintaining operator involvement and awareness in automatic processes.

The nuclear industry has recognized the need to provide more flexible automation to support operations and this has resulted in the development of several systems. In addition, new plant designers are developing AA systems for their highly automated plants. The systems are all operator commanded. While there is interest in other triggering conditions, near term systems are not likely to employ them. As experience is gained with AA systems and as industry standards and guidelines increasingly identify AA as a function allocation option, it is likely that AA applications will become more widespread.

5 EFFECTS OF ADAPTIVE AUTOMATION ON PERFORMANCE

In Section 3.2, the potential benefits of AA when compared with other types of automation were discussed. In this section, the evidence in support of AA will be examined. Specifically, whether the research and operational experience with AA supports the following hypotheses:

- AA will improve task performance relative to alternatives such as manual performance or static automation
- AA will improve SA
- AA will improve workload management (i.e., maintain workload at acceptable levels (not too high, low, or variable)
- AA will improve the detection of automation failure and management of recovery, including the maintenance of the skills needed to perform automation's tasks manually

5.1 Performing Normal Operations

The studies reviewed in this section were loosely grouped by the class of trigger (e.g., operator commanded, task performance, and OFS) used to change AA configurations.

In a study by Shaw et al., (2010), student participants controlled three unmanned aerial vehicles (UAVs). The task was to use unarmed UAVs to identify hostile targets and pass the information to the armed UAV. The armed UAV would then engage the target. There were three AA conditions:

- Manual condition – the operator sets waypoints, targets weapons, and launches them
- AA1 condition – the operator chooses between two LOA options: manual, and partial automation that initiates "scripts", such as a targeting script, and the task is performed automatically
- AA2 condition – the operator chooses between three LOA options: manual, partial automation (the same as AA1), and fully autonomous operations (in the latter, operators must approve weapons launch)

Changes in AA were triggered by operator command.

The performance measures included the percent of targets successfully tracked and the time participants took to handle an unexpected event automation could not deal with. Overall, the results showed that operators performed much better as more LOA choices were provided. AA2 offered the greatest number of choices and yielded the best performance. Shaw et al., suggested that increasing the automation options available to operators helps them manage their workload. Dealing with unexpected event performance did not differ significantly across conditions. In managing unexpected happenings, operators would increase the automation of unaffected aspects of UAV control, while assuming manual control of those affected. The authors interpreted the results as supporting the use of AA to improve task performance. However, the experimental manipulations do not provide a clean test. Since two AA conditions are compared to a manual condition, it is not clear whether performance improvements are the result of automation's adaptive characteristics or whether it is simply that the addition of automation itself improved performance.

Parasuraman et al. (2009) examined the effect of different types of automation for supervising multiple UAVs and unmanned ground vehicles (UGVs). University students performed tasks requiring change detection, planning routes, and communications in a simulated reconnaissance mission. Three conditions were compared: manual performance (no automation support), static automation (automated target recognition), and AA. The AA was triggered by task performance; operator detection performance was monitored, and automation was invoked when performance was below a predetermined setpoint. Measures of change detection (primary task performance), SA, and workload were obtained. To assess change detection, participants were asked to press a spacebar if the location of a previously identified target moved on a map. The SA measure was based on operator responses to verbal probes and represented as a single overall rating from 0 to 100. The workload measure was a single overall rating from 0 to 100 collected at the end of each scenario. The results indicated that the type of automation significantly affected the detection of change that was far better under both automation conditions compared with the manual one; furthermore, detection was better in the AA condition than in the static condition. The type of automation also significantly affected SA and workload. SA scores were significantly higher in both automation conditions than in the manual condition, although the two automation conditions did not differ significantly from each other. Workload was highest in the manual condition, followed by that under static automation, and lowest in the adaptive condition. The results of this study support the first three hypotheses stated at the beginning of this section: AA improved performance and SA and reduced workload.

Another study looking at the use of task performance to trigger automation changes was conducted by Calhoun, Ward, and Ruff (2011). They compared static automation and adaptive automation for supporting image analysis tasks while controlling a UAV. Participants performed a simulated UAV task that involved monitoring the status of multiple UAVs and analyzing information provided by them. Automation support for their tasks was provided based on operator performance on tasks such as image analysis and change detection. Performance on the tasks was monitored and integrated into a single score. When performance fell below a predetermined threshold, automation increased. When performance went above a predetermined threshold, automation decreased. The results showed that performance on an image analysis task was better in the AA condition. Performance on other primary tasks showed similar results, but not all achieved statistical significance. Participants' ratings indicated that workload and task difficulty were lower with AA. They also rated SA as higher in the AA condition.

In a follow-up study, Calhoun et al. (2012) evaluated the use of AA to support image analysis and decision tasks in a multiple UAV simulation. The trigger for the change in automation was task performance. The LOA was increased when task performance decreased, and decreased when performance improved. As in the previous study, participant performance with AA was compared with static automation. Dependent measures included task performance and participants' ratings of trust in automation, SA, and workload level. The results showed that task speed and accuracy was better in the AA condition than the static automation condition. Participants rated SA as higher when using AA and cognitive workload lower, although these differences failed to reach statistical significance. Static automation was rated higher in trust, but again the differences were not significant.

Miller, Miller, and Calhoun (2014) used a simulated UAV supervision task to compare participant performance of an image analysis task. Three LOAs (low, medium, and high automation support) were used with the level determined by the participant's performance score. Two methods of computing operator performance triggers were compared. In the first method, all tasks were considered equal. In the second method, task performance was adjusted based on weightings reflecting the tasks' priority and frequency. The authors hypothesized that adaptive automation support would be improved when the weighted scores were used. Non-professional operators controlled three UAVs and had to perform several related tasks, such as image analysis, target/UAV allocation, UAV rerouting, enemy aircraft detection, system health monitoring, and chat communications. The results did not reveal a significant difference in task performance or workload ratings between the two means of computing the triggers. However, post experiment questionnaires revealed that the participants favored the changes in automation based on the weighted trigger method and considered the changes in automation to be less disruptive.

Dijksterhuis et al., (2012) examined the use of performance-based triggers in a driving task. Experienced drivers performed a path-following navigation task in a driving simulator. In one condition, an adaptive lane position system provided an alert and then a warning if the driver did not respond when the system detected that the participant was deviating from their current lane. In a second condition, a non-adaptive system provided information to the driver as to lane position in a graphic display. The adaptive system was found more effective at improving lane-keeping performance (more time in the center of the lane and less lateral variation) than the non-adaptive system. However, it is noted that there is a confound in this study. The AA and static conditions are not directly comparable; since the AA used alerts to support performance while the static condition used a display. Alerts are more likely to direct driver attention to a problem, while the display does not. Therefore, whether the better performance in the AA condition is due to its adaptive characteristic or whether alerts are better than passive displays for this type of task is not known.

In another automotive study, Itoh and Inagaki (2014) examined three levels of support for vehicle collision avoidance. In the first condition, no automation support was provided. At the lowest level of automation, the system provided an alert to the driver. At the intermediate level, the system provided feedback to the driver that a lane change was not recommended. The feedback was in the form of a stiffer steering wheel. At the highest automation level, the system overrode the driver’s steering wheel maneuver and took control and steered the car to a safe position. A performance-based trigger was used based on longitudinal distance from a passing vehicle and steering wheel rotation (in the direction of a passing vehicle). Skilled drivers participated in driving scenarios in a motion-based simulator. The dependent variables were the number of collisions and the distance between the drivers and the other car. Ratings of the participants’ acceptance of the system were also obtained. The results revealed that the highest automation level was most effective and the low and intermediate LOAs yielded similar results. Interestingly, even though participants found all the systems acceptable, the subjective ratings for the highest level of automation was lower than the other two suggesting that participants did not like automation overriding their decisions. Like the study discussed above, the conclusion must be regarded as tentative. While three AA conditions are compared to a manual condition, there is no static automation control group. Therefore, where the observed effect is due to the adaptive aspects of automation or whether it is simply due to providing automation (static or adaptive) is not known.

OFS triggers are typically based on assessments of workload, SA, and fatigue. AA researchers have used physiological parameters as one approach to assessing such states. Psychophysiological measures have been found to be generally sensitive to changes in states such as mental workload and fatigue (Wilson & Russell, 2007). Further, they can provide information about operator states in real time.

Sebok et al. (2003) examined the use of AA support for students performing a compensatory tracking task. Electroencephalogram (EEG) measurements were used to assess participant workload and to initiate AA support. The EEGs were obtained as participants performed a secondary task. There were three groups: The first group performed the task manually until the EEG measures indicated a rise in workload at which time AA support was provided. The second was a yoked control group that received AA support on the same schedule as the AA group; however, the support was not adaptive (not associated with a change in the participant's workload). In a third condition, task support was received randomly. In addition to tracking performance, subjective workload was assessed. The results indicated that the AA group performed better on the tracking task than either of the two control groups. The pattern of results was the same for the subjective workload scores. Subjective workload was lower for the AA group when compared with the other two groups. These findings show the potential to use EEG to detect operator workload changes in real-time and the use of AA as a compensatory means to control workload by using automation to support task performance.

Imants and de Greef (2014) conducted a study of simulated air traffic control (ATC) scenarios with "naïve participants" who were trained on the tasks. They tested the feasibility of using eye metrics to both determine what tasks air traffic controllers were currently performing and their workload. Identifying current tasks is important to minimize distractions since automation can be applied to the operator's ongoing activity and to minimize automation surprises. Therefore, eye metrics may be effective triggers to determine context sensitive operator support (based on current tasks) when needed (based on current workload). The study did not involve the actual use of the metrics to dynamically change automation. The result indicated that some of the metrics were successful at task identification and others were sensitive to workload. No single metric supported both task and workload determination.

The effectiveness of using multiple physiological measures was examined in a study where participants controlled four UAVs in a simulation environment (Wilson & Russell, 2007). Their task was to locate and identify targets to bomb using a set of predefined rules. In one condition, operators were not aided in this task. In the other, operators were aided by the system in two ways. First, the target speed was reduced providing increased time for evaluation. Second, vehicle health messages were displayed in a drop tab rather than on a separate display, thus reducing access time and memory load. Whether the aid was provided was based on the OFS, which was assessed using the following physiological parameters: EEG, electrocardiograph (ECG), and vertical and horizontal electrooculography (EOG) activity. When OFS was above a predefined threshold, the aid was provided. The effect of adaptive aiding on task performance was evaluated. The results showed that task performance was improved by 50% when aiding was provided. Like several of the other studies reviewed, conclusions about the effectiveness of AA are limited by the experimental design. Since AA is only compared to a manual condition, the superior performance of the AA group may simply have been an effect of supporting task performance with automation, rather than AA.

Wilson & Russell (2007) noted that physiological measures can change rapidly; therefore, designers need to be careful when using them to trigger automation configuration changes. If the configuration changes occur too rapidly, they may interfere with task performance. Wilson and Russell also noted that significant improvement in system performance and safety can be obtained by assessing OFS since, while other aspects of the system are monitored for degraded conditions, the operator is not. Real-time monitoring of OFS can address this issue.

Wilson & Russell also noted that one of the challenges in the use of physiological measures is workload assessment. Byrne and Parasuraman (1996) discussed additional challenges that arise using psychophysiological measures in the control of AA. These measures must be sensitive to workload changes in the specific task environment (e.g., discriminate between task load levels) and be relatively unobtrusive. The sensitivity of psychophysiological measures can be affected by other factors such as the operator's emotional states, activities (i.e., speaking), and the environment in which measures are obtained. They also must be assessed for the effects of individual differences. The challenges posed may suggest the use of a hybrid approach where different triggers are used to provide the robustness that may be lacking in individual measures.

Workload can be measured in ways other than physiological parameters. The following study assessed workload using a secondary task methodology (Kaber et al., 2005). Secondary task assessments of workload have long been used in general workload studies (Wickens et al., 2004).[9] In this study, student participants took part in a simulated ATC task. AA was applied separately to support different cognitive aspects of the ATC task. Using Parasuraman's et al. (2000) categorization of cognitive functions, the task of clearing an aircraft for landing was divided into its information acquisition, information analysis, decision-making, and action implementation components. Automation was adaptively implemented using workload as a trigger. Participants' workload was measured using performance on the secondary task, specifically a gauge monitoring task. Consistent with secondary task methodology, the task was unrelated to the ATC tasks and was performed only when the participant could do so without impacting the primary task of clearing aircraft for landing. When performance of the secondary task was below a predefined threshold (indicating a high workload), automation was introduced. Above a predefine threshold (indicating a low workload), the automation was stopped, and the participants performed the task manually. The results showed that the participants' performance was better when AA was applied to the lower-level cognitive functions of acquiring information and implementing actions. By comparison, automation was less effective when applied to higher-level cognitive functions of information analysis and decision making. These findings are important in that they suggest that the benefits of AA may depend on which cognitive aspects of the task are supported.

The studies described below used task load as an indicator of workload (i.e., automation changes were triggered by changes in task load). Task load is a surrogate for workload because it is based on the amount of work operators must perform, such as the number of targets they must process per unit time, rather than a direct measure of workload. The assumption is that as the amount of information an operator needs to process goes up, workload goes up. Therefore, if the task load goes up, automation can be provided to lower workload.

In one study, students performed simulated UGV reconnaissance missions and were required to detect changes in a situation map and identify hostile targets (Cosenzo et al., 2010). There were three automation conditions: manual, static automation (semi-autonomous), or adaptive automation. In the adaptive condition, the level of automation provided was based on task load (i.e., the total number of targets on the display). In addition to change detection and threat

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[9] The primary assumption of secondary task methodology is that human operators have a finite quantity of cognitive resources available to perform their primary tasks. That portion of the capacity not required for primary task performance is available as spare capacity for other, secondary tasks. The workload imposed by a primary task may be determined by measuring the speed and accuracy of a secondary task since it can only be performed with the mental capacity not used by the primary task. The more capacity needed for the primary task, the less is available for the secondary task and it will be performed less well. When performance on the primary task is maintained, a decrease in performance of the secondary task reflects higher workload of the primary task.

identification performance, the National Aeronautics and Space Administration's (NASA) Task Load Index (TLX) was used to obtain workload measures and SA was assessed based on the participant's responses to queries about the current situation asked during the scenarios. Results showed that when task load increased from low to high: (1) threat detection performance degradation was less in manual and adaptive than in the static condition, (2) no differences in change detection was found, and (3) SA performance was better in the both automation conditions than the manual condition. When task load shifted from high to low: threat detection performance was better in the adaptive than the other two conditions, and no differences in change detection and SA were found. No significant effects on workload were found. The authors suggest that the lack of a workload effect may be attributable to high task demand levels even in the low task load condition.

In a follow-up to this study, Reinerman-Jones et al. (2011) examined the effect of the congruence between task demands and levels of automation on performance. Automation was either statically or dynamically provided. Students performed tasks like those described in the Cosenzo study described above. The result showed that higher-levels of automation were beneficial regardless of task load. They further found that the task switching associated with AA was detrimental to performance under high task-load conditions. This finding was attributed to the potential effects of the distraction caused by such changes during a period when operators were already very busy.

The results of these two studies are complicated and provide mixed results regarding the effectiveness of AA.

In another study, student participants performed a target detection task in a high-fidelity multi-unmanned vehicle (UV) simulation (de Visser & Parasuraman, 2011). Three levels of automation were used: manual, static and adaptive. AA was used only when task load was high (i.e., the number of UVs controlled was high relative to the low task load situation). Dependent measures were detection accuracy, detection time, trust in automation, self-confidence, SA, and workload. While no difference is detection performance was obtained, the results showed benefits for AA compared with static automation and manual performance for SAs, self-confidence, workload, and trust. The authors noted that participants rated the automation as slightly more trustworthy when aiding was implemented in a context-sensitive manner (when high task load was high), rather than when it was continually present (static automation).

In the studies discussed so far, AA configuration shifts were based on single categories of triggering mechanisms. In the studies reviewed below, hybrid triggers were used. As noted above in Section 3.3.2, hybrid triggers may have the potential to be more effective at capturing OFS, since weaknesses in one method can be overcome by having alternative methods to use.

Kidwell et al. (2012) examined automation support for the supervision of multiple autonomous vehicles. The student participants performed tasks including image analysis, target detection, and vehicle routing. There were three LOAs support for these tasks: low, medium, and high. Changes in AA were triggered by either operator command or participants' task performance. Depending on the trigger, participants either requested a change in LOA or the change occurred automatically as performance changed. The dependent measures were task performance, workload, and ratings of confidence. The results showed that in comparison to the performance-based trigger, operator commanded changes increased task performance and confidence. However, workload was increased as well. The authors suggested that when operators make decisions to change the configuration, it keeps them in-the-loop. While this increases workload, it also reduces the unpredictability of the system.

The next two studies examined the feasibility of using multiple metrics to predict variables that can be used to trigger changes in AA configurations. The first study looked at predicting operator workload and the second at task performance. Note that these feasibility studies did not use the proposed triggers to change AA configurations during task performance.

Boeke et al., (2015) examined the relationship between potential trigger classes in a simulated UAV supervision task: objective measures of workload (secondary task performance), subjective workload ratings (NASA TLX), task performance (target surveillance), and physiology measures (EOG and ECG). Automation was not manipulated in this study; task difficulty was in order to create workload variations that would permit examination of the relationship between these potential classes of triggers. Participants supervised the UAV in a simulated environment. Based on the results, the authors recommend the use of measures of objective workload as the primary means of triggering shifts in AA and that performance and physiological measure should be used to adjust the changes. Therefore, a hybrid approach to assessing operator workload was recommended.

Lackey et al., (2015) examined whether the combination of physiological and subjective parameters could predict performance. The physiological parameters included EEG, ECG, functional near-infrared spectroscopy, transcranial doppler, and eye tracking sensors. The subjective parameter was a simple workload rating using the Instantaneous Self-Assessment scale. Undergraduate student participants performed simulated UAV supervision scenarios that required change detection and threat detection tasks. Like the Boeke study, overall task difficulty was varied in three conditions: low, medium, and high difficulty. The results indicated that regression models successfully predicted task performance based on the physiological and subjective workload measures. Therefore, using such measures may be useful to trigger a shift to AA configurations based on anticipated performance changes.

The studies to follow discuss the use of hybrid approaches to triggering AA configuration shifts.

Li et al., (2013) examined two levels of AA to support simulated teleoperations involving moving a robot arm to a specified position such as in a payload operation. Student participants completed teleoperation scenarios and were responsible for trajectory planning, selection and adjustment of cameras, and operating the arm with hand controllers. Two types of automation support were used: collision avoidance and trajectory control. Each of these forms of support had two adaptive levels: guidance and control. The change in DOA was based on a hybrid trigger approach. The change could be commanded by the operator or triggered by changes in task performance. Operators could override the system triggered changes in DOA.

In addition to the hybrid AA condition, several other conditions were tested: a static allocation condition, an operator commanded trigger condition, and a performance trigger condition. The dependent measures included task performance (time and accuracy), process measures (management of automation levels), awareness of automation configurations, and the operator's workload.

The results generally favored the hybrid AA system. It led to better performance and lower workload. This study supported the use of AA to improve performance and the use of hybrid triggers to shift automation configurations. The participants subjectively preferred the hybrid AA condition more that the operator commanded or performance triggering condition alone. It was also preferred over the static allocation condition.

When asked about preference of the two types of triggers, participants preferred operator commanded changes to performance-based triggers. The reasons given were an increased feeling of control over the automation and a reduction in occasional confusion experienced when performance triggered changes in automation unexpectedly.

Ting et al., (2010) developed a hybrid indicator of OFS based on the physiological parameters of ECG and EEG. Graduate students operated a simulated cabin air management system. The operator monitored the performance of system controllers to ensure a sufficient quantity and quality of breathable air. The operators could make adjustments by controlling system parameters such as oxygen levels, temperature, and humidity. Each had a normal operating range. The DOA was adaptively varied. Higher DOAs were characterized by a greater number of system parameters that are controlled automatically. A total of five different DOAs were available. Adaptive control was compared with a non-adaptive automation based on an error-triggered system. Task performance was improved with the AA system, as was performance on a secondary task, and subjective strain was reduced. The authors concluded that the hybrid trigger could be used effectively to control automation configuration shifts.

Saqer et al., (2011) examined whether an assessment of baseline task performance and working memory capacity can predict performance when the task is supported by automation. That is, can these measures be used as a hybrid trigger of AA changes? Student participants performed an air defense task in a simulation UAV environment. They had to identify and destroy enemy targets. Three levels of automation were provided to support this task: no automation, low AA and high AA. Two levels of task demands were also used based on the total number of targets presented. The results showed that the baseline measure of performance was predictive of AA supported performance. The measure of working memory capacity, while not predictive of task performance, did predict how effectively participants could use the automated aids. Those with higher memory capacity scores used the aids more effectively. The authors note that these factors are easy to obtain and can be used to efficiently trigger AA.

The studies discussed thus far used a variety of different triggering conditions to change AA’s configurations. There are also studies discussed in the AA literature where changes in AA configurations are made on a predefined schedule. This method of changing automation does not fit the definition of AA because the triggering condition is not related to change in operator functional state, plant state, or any other trigger. Such an approach can potentially lead to changes in automation that are contrary to the purposes of AA, such as lowering the level of automation when operator workload increases. However, these studies do provide some insight into the exposure of operators to changing automation configurations.

In a study by Kaber and Endsley (2003), student participants performed a dual-task scenario involving a dynamic target tracking and elimination task, and a secondary monitoring task. Low, intermediate, and high-levels of automation were used that were allocated dynamically. The LOAs were varied according to a predefined schedule. The dynamic allocation was compared to a manual condition and fully automatic operations. Performance measures included task performance, SA, and workload. The results showed that the LOA was the primary determinant of primary task performance and SA. Low levels of automation evoked superior performance, while intermediate levels facilitated higher SA. AA was the determining factor in workload and secondary-task performance. In general, the results support intermediate LOAs and AA.

McGarry, Rovire, and Parasuraman (2005) varied information and decision automation across segments of a simulated battlefield engagement. The participant’s task was to identify the most dangerous enemy units and to decide which friendly unit should engage them. The variations in automation were based on a predefined schedule, and some segments required participants to complete tasks manually. These authors found that the accuracy of the participants' decisions improved in segments with decision automation when they were preceded by segments with information automation. Exposing users to periods of information, automation minimized some problems associated with imperfect decision automation.

One concern with AA is the potential disruption in performance due to the shift between automation configurations. This issue was examined by Di Nocera, Camilli and Terenzi (2007). Students played the video game Tetris™ under three levels of difficulty in either manual or automatic mode. The automation gave a projection of the falling block on the lowest level. In some trials the automation level shifted, while in others it did not. The shift followed a predefined schedule. The player's performances and workloads were impacted by the shifts. A shift in either direction (automatic to manual and manual to automatic) disrupted the ongoing cognitive activity involved in mental rotation; the shifts also were affected by task load. Better performance occurred when shifting from manual to automatic in the high-difficulty task, while the reverse was true for the low difficulty task (the intermediate difficulty task did not significantly differ from the other two). However, since the shift was based on a schedule rather than specific triggering criteria, the shifts might not have occurred at an optimum time, and this may have disrupted performance.

Jou, Yenn, and Yang (2011) examined the effects of differing levels of automation on performance in a simulated NPP reactor shutdown task performed by graduate students. Five levels were used. The levels differed in the amount of time spent with full automation. At the lowest level, participants received operational guidance from the system, but tasks themselves were performed manually. This is equivalent to the ABWR semi-automatic level of automation. At the highest level, the task was performed with a fully automatic level of automation. The changes in automation were based on a predetermined schedule. The results generally showed that higher levels of automation led to better task performance and lower workload, but poorer SA.

While studies of changing DOA based on a predefined schedule are not AA by the definition, they do show that exposing operators to different DOAs is beneficial. This result is consistent with research on exposure to different DOAs in general (not within the context of AA). In one such study, Ryser (2003) found a positive effect of exposing operators to varying LOA in a study examining the relationship between DOA, strategies applied by operators, and mental representation of the system. The participants were trainee operators who performed methanol-synthesis tasks in a simulated chemical plant. Some participants were trained primarily under manual-control conditions, a second group under high-automation conditions, and a third group experienced varying levels of automation in different trials. The LOAs were not changed dynamically. The results showed that participants from the third group developed a better understanding of the role of automation than those from the other two groups.

When not changing the AA configuration based on a predefined schedule or operator command, an important consideration to take is when specifically, the triggering condition causes a shift in the AA's configuration (i.e., the 'invoking threshold"). Taylor et al. (2013) noted that changing the level of automation while an operator is performing a task can negatively impact performance. Therefore, configurations should not necessarily change immediately upon detecting a change in the triggering condition. Taylor suggests that "introducing a slight delay before changing the level of automation provides the system with adequate time to ensure that the newly detected state will persist, avoiding the risk of changing the level of automation (temporarily reducing operator performance) to meet a fleeting level of demand."

Another consideration is the effect of a configuration change on SA and workload. As task load increases, changes in workload and SA are not linearly related (Rusnock & Geiger, 2013). That is, for certain task loads, increasing automation leads to increases in both workload and SA, while for others, workload increases but not SA. Table 5-1 illustrates the relationship between SA and workload under different DOAs. This suggests that designers need to select invoking thresholds that achieve the desired changes in workload *and* SA.

Table 5-1 Relationship of SA and Workload for Different DOAs

Correlation of SA & Workload	**Low Workload**	**High Workload**
Low SA	High DOA (Low Vigilance)	Low-Intermediate DOA and Automation Failure
High SA	Intermediate-High DOA	Low DOA

So far, the effects of AA on performance using a variety of triggering conditions have been discussed. An additional consideration when implementing AA is the relationship between the cognitive demands of the task and the type of support provided by automation. While we suspect this relationship may be the cause of some of the inconsistent findings discussed above, one study specifically examined this relationship. Taylor et al. (2013) looked at the impact of AA on supporting task performance from the perspective of the types of cognitive demands the tasks impose. They hypothesized that AA would support performance when the type of support provided by AA matched the specific cognitive demands of the task. Where a mismatch exists, providing automation would not enhance performance. To test this hypothesis, students operated a simulated UGV and were required to perform three tasks: driving the vehicle, detecting threats, and detecting changes in a situation map. In some trials the automation supported the specific cognitive demands of the tasks and in others it did not. Further, some of the trial's automation was statistically provided while in others it was adaptively provided based on overall task demand (e.g., the number of threats to detect). Measures of task performance and workload were obtained.

The results supported Taylor et al.'s hypothesis. AA effectively supported task performance in the trials where it was matched to the cognitive demands of the task and performance was greater than when static automation was available. When automation and demands were not well matched, automation was much less effective and sometimes caused increases in workload. The authors attributed the latter finding to the distracting effects of automation that otherwise was not sufficiently useful to aid performance.

The studies reviewed above focused on the effects of AA on normal operations as reflected in measures such as task performance, SA, and workload.

5.2 Managing Degraded Conditions

This section deals with the ability of operators to monitor automation, detect when automation degrades, and manage the degraded condition to restore and maintain system integrity. From prior research, operators can be poor at monitoring reliable automation and this has led to significant production and safety issues (O'Hara & Higgins, 2010). The issue of monitoring failed automation in greater detail will be examined, followed by the evaluation of the role, if any, AA plays in supporting operator management of automation failures.

Automation's degradation and failure (D/F) falls on a continuum from degradations resulting in little to no loss of functionality at one end of the continuum to a complete loss of functionality, and automation failure, at the other (O'Hara, Gunther & Martinez-Guridi, 2010). In a degraded condition, automation may continue to operate, but the loss of functionality may lead to performance problems. In a failed condition, automation does not perform its function at all.

D/Fs can lead to two types of problems for operators:

- automation does not do what it is supposed to do when it should
- automation does something that it is not supposed to do, such as causing abnormal operating conditions due to erroneous automatic action, and/or providing erroneous information

When these issues arise, operators must detect automation's D/F condition, assess the situation, plan responses (determining the proper actions to take), and implement those actions by restoring the automation or transitioning to back-up systems.

To address this question, Wickens (Wickens, Li, Santamaria, Sebok & Sarter, 2010) conducted a meta-analysis of studies that examined automation failure detection. Specifically, they looked at overall performance when automation worked as designed, and performance when the automation failed. An expansion of this meta-analysis to 18 studies was later reported in a subsequent study (Onnasch, Wickens, Li & Manzey, 2014). This report integrates the results of both studies.

Wickens and colleagues examined the operator's ability to detect automation failure as a function of DOA. As defined by Wickens' analysis, DOA represents a combination of two automation dimensions: LOA and stages of information processing (generic tasks in our characterization). Lower DOAs reflect automation applied to earlier stages (information acquisition and information analysis) and higher DOAs when automation is applied to later stages (action selection and action implementation). Therefore, the DOA is higher when the LOA is higher, and the stages of information processing are later.

The meta-analyses revealed an interesting relationship between DOA and automation failure detection. Wickens called this relationship the "routine-failure tradeoff." The tradeoff suggests that when automation functions as it is supposed to (routine), higher DOAs lead to better human-system performance. However, when automation fails, the higher DOAs lead to poorer human-system performance. This relationship is illustrated in Figure 5-1. The tradeoff is acceptable until Point A in the figure. However, as the DOA is increased beyond Point A, the negative effects of failure on performance become significant. The routine-failure tradeoff has been identified by others as well (Smith & Jamieson, 2012).

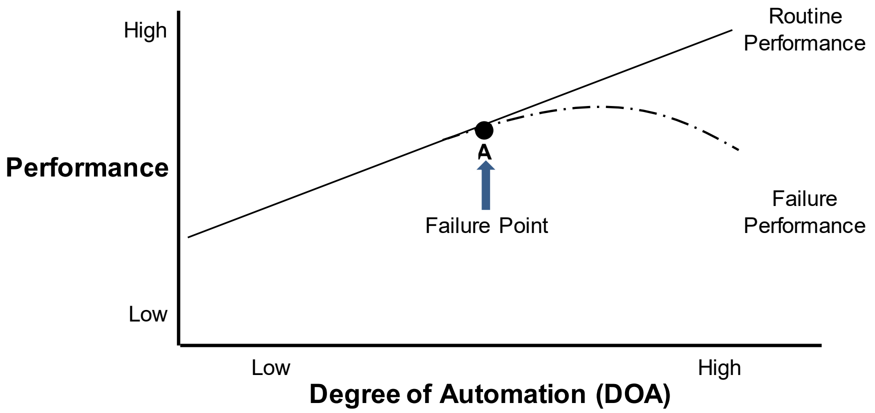

Figure 5-1 Routine-failure performance tradeoff
(adapted from Onnasch et al., 2014)

As for why this tradeoff exists, Wickens suggests that in the routine condition, as DOA increases, operator workload is reduced since the operator is relieved from the responsibility to perform functions that automation performs, and the operator can attend to other aspects of system performance. Overall system performance is improved since the workload reduction afforded by the lower workload results in cognitive resources being available to assess overall performance.

This very situation works against operators when automation begins to fail. That is, since the lower workload shifts the operator's attention away from the automation and the functions it controls, it reduces the operator's SA about the automation's performance, thus degradations go unnoticed (Dixon & Wickens, 2006; Wickens et al., 2010). The higher the DOA, the worse the situation. At lower DOAs, operators must still attend to some aspects of automation and the tasks to be performed. Since the operators are still engaged in these tasks to some degree, there is SA regarding the automation's performance and detection of degradations is more likely. Therefore, when DOA is high and automation fails, SA regarding automation and its tasks is low and workload ramps up as operators try to recover SA, plan actions, and implement tasks to recover. Figure 5-2 illustrates the effects of DOA on task performance, SA, and workload as automation fails.

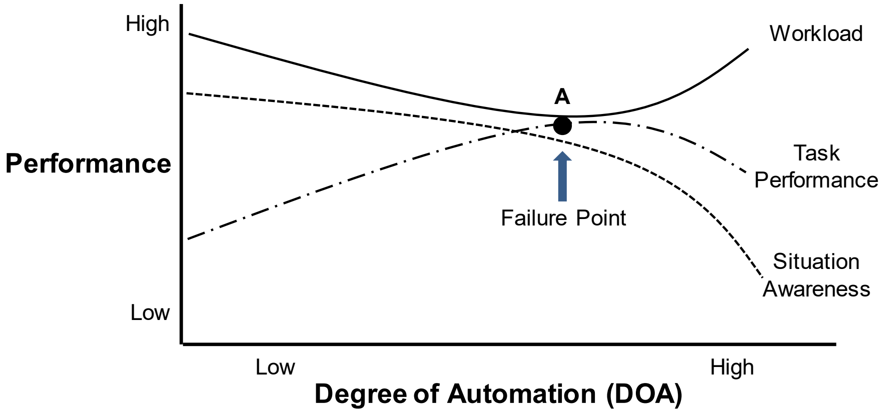

Figure 5-2 Hypothesized changes in task performance, SA, and workload as a function of degree of automation when automation fails

This simple relationship becomes even more complicated when reliability is considered. Operators are less likely to monitor automation they consider reliable. This situation is considered “overtrust” and is likely to be the root cause for this finding.

In summary, Wickens analysis shows that higher DOAs can lead to performance issues when automation fails due to loss of SA. There appears to be a critical DOA point beyond which failure recovery is very difficult. Wickens suggested that as designers make decisions about automating tasks, they should assess this performance tradeoff in the light of automation failure probabilities. That is, there may be a point where the cost of increasing the DOA is too great if the automation fails. This is especially significant if operators are expected to provide manual recovery for failed automation.

Once operators realize the automation is degrading or failing, they face significant challenges. Such unplanned transitions from automatic to manual control create periods of very high workload (Huey & Wickens, 1993). The shift often requires a change in the concept of operations (ConOps) wherein the roles and responsibilities of individual crewmembers must change to compensate for the loss of automation (Roth & O'Hara, 1999, 2002).

One approach to managing this tradeoff may be to refrain from higher levels of automation (Kaber & Endsley, 2004). There is some empirical support for this approach. Petermeijer et al. (2015) found greater negative effects on lane-keeping driving performance associated with a driving aid providing continuous guidance as compared to others that provided less guidance and required drivers to lane keep on their own some of the time.

In another study, Lorenz et al. (2001) examined the effect of LOA on out-of-the-loop problems. Students performed environmental control tasks with the support of an intelligent fault management (IFM) system. The IFM had three LOAs. In the lowest, it guides operators on how to find faults. In the medium LOA, the system made a fault diagnosis and recommended actions to take. At the highest level, the IFM made a diagnosis, recommended actions, and automatically implemented them unless the operator disagreed and overrode the action within 45 seconds. The IFM failed (provided no support to the operator) in 10 percent of the trials during which the participants’ fault detection and management performance was evaluated. The results showed degraded performance in the medium and high LOAs, but more consistent performance when the IFM system having a low LOA failed. This failure was due, in part, to changes in information-sampling strategies with changing LOA. This study found that higher LOAs were associated with more human-automation issues. Recovery from automation failure was better at the lower LOAs. This finding is generally consistent with Parasuraman recommendation that recovery from automation failure is superior when intermediate levels of automation are used rather than high automation (Parasuraman, Sheridan & Wickens, 2000).

Manzey, Reichenbach and Onnasch (2008) investigated the effects on fault identification and management performance of four different levels of automation. In the first level, there was no automation, and the entire task was handled manually. In the second level, the automation offered a diagnosis of system faults. The third level provided diagnosis along with recommended actions that the operator had to perform manually. In the fourth level, the diagnosis and actions were automatically performed upon operator’s approval. Student participants controlled a simulated spacecraft life-support system in which malfunctions occurred. Measures were collected of primary- and secondary-task performance. Primary task measures included percentage of correct diagnosis and fault identification time. The secondary task measure was connection check response time. Automation bias (commission errors -

doing what automation suggests even when it is wrong) was also assessed. The authors also examined “return-to-manual control” (skills deficit) after the automation failed. They found that any automation improved primary- and secondary-task performance compared with manual operation, and the higher the LOA, the better the performance. In using the two lower levels of automation, differences were observed in secondary task performance, but not primary tasks. A cost was incurred however; automation bias was observed in approximately 50% of the possible opportunities and was about equal for all automation functions. The authors suggested that these errors were due to less attentive crosschecking of information with automation. Therefore, a partial explanation of the improved performance at higher levels of automation may be that participants unquestioningly accepted the automation’s actions. In addition, there was some evidence of loss of control skills at the highest LOA, the only one for which automation control was available. The authors concluded that medium LOAs are preferred if manual skills must be maintained.

These findings may partially explain the preference that experienced pilots have for a management-by-consent approach to automation, where automation cannot act unless and until explicit pilot consent is received (Olson & Sarta, 1998 & 2001). Operators rarely want to delegate whole tasks or functions to automation; more typically, they want to delegate some portion of them (e.g., the information-gathering portions of a task (Miller, 2005)).

Thus, intermediate and low DOAs support automation failure detection and management, especially when manual skills need to be preserved. This approach may also be favored by operators of real-world systems. In addition to improving SA, failure recovery, skills maintenance, and lower DOAs also keep the operator in a clear position of control.

Another approach to support automation failure recovery performance may be to use AA that provides operators with experience with various DOAs, which, as noted previously, enhances the operators understanding of how automation performs.

A study by Parasuraman, Mouloua, and Molloy (1996) examined this hypothesis. They examined the effects of AA on automation failure detection during flight simulation scenarios performed by nonprofessionals. Participants monitored engine status while engaged in tracking and fuel management tasks. The engine status was monitored automatically; however, the task was shifted to the participants periodically. Two methods of shifting the task were used. The first shifted task responsibility between automated and manual monitoring was based on a predefined schedule. The second method followed the same schedule, but only returned monitoring to automation if the participant’s manual performance did not meet the predefined criteria. There was a third group where the monitoring task was always automated. At some point during the scenarios, the automation failed and the ability of participants to detect the failure was the key performance measure. The results showed that monitoring performance significantly improved (by approximately 66%) following the time period where the task was performed manually. The authors interpret this finding as demonstrating the effectiveness of AA to support failure detection.

This was the only study found at the time that provided a specific test of AA’s impact of failure management. Therefore, there is some support, but it is quite limited.

There are some other factors that may contribute to automation failure management: task sharing, HSI design, and training.

AA may be more effective if it is implemented to support task sharing. This is because a factor contributing to the failure to properly monitor automation is that automation often performs tasks independently from plant personnel (O'Hara & Higgins, 2010). Personnel often have other tasks for which they are responsible. While personnel do play a role in monitoring the performance of the automation, that responsibility often becomes compromised in the face of workload pressures. This problem is exacerbated when automation is reliable, and personnel trust and depend on it to function properly (Parasuraman & Riley, 1997). Because of workload management strategies, personnel may continue to use automation, even when it does not correctly fulfill its functions. Improved task sharing strategies may help overcome this issue.

HSI design is another contributing factor to difficulties dealing with automation failures. Even when operators do monitor automation, the design of the HSI may not support monitoring needs. Many studies have found that HSIs typically provide insufficient information about automation's goals, current activities, and performance (Liu, Nakata & Furuta, 2004; Lee & See, 2004; Parasuraman & Riley, 1997; Roth et al., 2004; Rook & McDonnell, 1993). Willems and Heiney (2002) stated, "as errors involving automation tend to be more cataclysmic and costly, the human interface has become more important than ever."

Consistent with this finding, Parasuraman and Riley (1997) noted that there is evidence to indicate that automation failures were better detected when the behavior of automation can be easily determined in the HSIs, especially those that minimize attentional demands (such as integrated displays and emergent features.

An additional factor to consider is training. Training supports operators' ability to detect and respond to degradations and failures (O'Hara & Higgins, 2010). Training can provide operators with clear and specific information so that when automation degrades and fails, the following occurs:

Operators -

- understand how and why it might degrade or fail
- understand the implications of such degradations for HSI and their own performance
- monitor the system's performance so they can detect and recognize degradations via control room HSIs
- perform recovery- and compensatory-actions
- transition smoothly to backup systems when needed
- understand how the roles and responsibilities of crew members and the concept of operations are affected

Further, simulator training that specifically gives operators experience with examples of automation failures helps them to deal effectively with any failures (O'Hara & Higgins, 2010).

5.3 Conclusions

5.3.1 Task Performance, SA, and workload

In general, AA supports improved task performance. There are exceptions however, but the research does not provide a basis to understand why. There is a thought that it has to do with a mismatch of task demands and automation support in some studies. This was found in one study but may have been a factor in other studies that did not specifically address it. For example, operator performance was better when AA was applied to the lower-level cognitive

functions, such as acquiring information and implementing actions, and less effective when applied to higher-level cognitive functions of information analysis and decision-making. When task demands and automation support are not well matched, changes in automation are likely to be distracting and increase workload.
In general, operators do well with high DOAs in AA systems. This may be because exposure to varying DOAs improves their understanding of how automation functions. In fact, exposing operators to different LOAs has been found to be beneficial.

The effects of AA on SA and workload are a bit more complicated. Some studies did find improved SA. However, others did not. This result may be dependent of the specific nature of the tasks. When AA and operators share tasks, SA may be improved. But when AA is performing a different set of tasks, operator SA for those tasks may be reduced. Our effort to understand the effects of AA on SA was hampered by the fact that many studies that assessed SA were not specific about the aspects of SA that were measured. That is, it is not often known if the SA measures assessed the operator's SA of overall system status, SA of what automation was doing, or both.

The results on the effects of AA on workload are similarly complex. Some studies found it lowered workload while others did not. One reason for this has to do with what AA is being compared with. If AA is compared to a manual condition, workload is likely to be lower. If AA is compared with a static automation condition, workload is likely to be higher. Also, as mentioned above, if automation support is not well matched to the task demands, automation shifts can be distracting and increase workload as the operator must figure out what automation is doing. Workload increases can be associated with performance improvements, so the tradeoff may be acceptable in some circumstances.

One key to successful application of AA is the triggering conditions that cause shifts in automation configurations. The research reviewed provided some insights into the effectiveness and limitations.

Operators generally preferred operator commanded triggers. Operator commanded triggers keep the operator in control of the system and reduces potential surprises and distractions that can occur when a configuration shift occurs that the operator did not expect. However, operator commanded triggers can increase workload since operator actions are required to change the DOA. This may be problematic when they want to initiate automation because their workload is already high. Therefore, when operator-initiated triggers are used, designers should seek to minimize the workload associated with them. The cognitive cost of initiating automation changes should not outweigh its benefits or operators may not use it (Parasuraman et al., 2009). This concern can be addressed with well-designed HSIs. While workload is created by operator commanded triggers, the workload contribution is less than if the task had to be performed manually.

The other triggering categories, such as assessments of task performance, OFS, and task load, were also effective. They have minimal effect on workload, because operator action is not required. They all have the potential to cause disorientation and distractions that can lead to transient performance decrements. When these triggers are used, HSIs should be designed to alert operators to the change in a manner that minimizes distractions and interruptions.

Results were found with using task performance as a trigger. Operators do not have to request a change in automation when task performance is used, therefore, it does not contribute to workload. A negative aspect of using task performance is that a decline in performance is

needed before the DOA is changed. Triggers that predict a downturn in performance before it occurs have the advantage of anticipating impending performance decrements and the potential to mitigate them before they occur; OFS triggers have that potential.
OFS, especially as assessed by physiological measures, has had some success. However, technical challenges were noted, including:

- the potential for physiological variables to change very rapidly
- integrating variables over time to get reasonable invoking thresholds
- interference and noise from other physical activity such as moving around
- uncertain viability in the operational environment of a control room

Resolving these issues would be a significant advantage because it would provide an unobtrusive way to assess OFS issues and increase automation in advance of performance decrements. This could be accomplished at no cost to workload.

Researchers have suggested that there is value in using a hybrid approach to triggering AA configuration changes. Hybrid approaches may provide a more robust approach to determining when changes should be initiated. The use of multiple approaches to trigger automation changes helps offset limitations of any single approach. The limited research available provides support for this hypothesis. However, not enough research is available to recommend which triggering categories should be used.

For any triggering condition except operator command, an important decision is the identification of an appropriate invoking threshold; the specific point at which the trigger changes the AA configuration. The research reviewed provided very little insight into the process of determining invoking thresholds. It did however highlight some concerns. One is the potential for triggers to oscillate around the threshold. For example, if physiological measures are used to change automation, these measures can potentially move up and down about the invoking threshold. The danger here is that it can cause oscillations in automation configurations. This type of oscillation is unlikely to be acceptable to operators and is likely to disrupt performance. Strategies to manage this issue are needed. Perhaps an approach can be found in methods used to address “chattering” alarms (O’Hara & Brown, 1999); when an alarmed parameter drifts above and below the alarm setpoint rapidly indicating an alarm state and a return to normal.

Another important consideration in the design of AA systems is the number of configurations the system has, and the length the minimum time configurations should remain active. The research provided few answers to these questions. Studies of Flight Management Systems (FMSs) suggest that too many configurations can make it difficult for pilots to develop a good understanding of the relative roles and responsibilities of the crew and the automation for each. This concern is related to HSI design (supporting configuration awareness) and training on the automation. However, it appears there is a point where there may be too many configurations.

The other consideration, related to the invoking threshold discussion above, is the minimum time a configuration should be active. Several researchers have suggested that rapidly changing configurations will be disruptive to operators. However, the research does not provide any suggestions as to what that time is.

In summary, the research provided some insights into the effects of AA on performance, SA, and workload. It also provided an improved understanding of the detailed design of AA systems. However, additional research is needed.

It was noted that deriving conclusions about the effects of AA was sometimes hampered by experimental designs that did not provide a clean test of AA. Where applicable, these issues were identified. Future studies should ensure that their designs support the assessment of the hypotheses they are designed to test. For example, if the focus is on the effects of AA, comparing AA to manual conditions alone in not adequate to test the hypothesis. The results of such comparisons make it difficult to distinguish between the effects of AA or those of task automation, whether static or adaptive.

5.3.2 Detection of Automation Failure and Management of Recovery

Information to address the potential of AA to support the operator's ability to detect automation failures and manage them was sought. However, very little research specifically addressed this question. The research that was reviewed tentatively supported a conclusion that it does.

The general issue of automation failure management was examined. Wickens' meta-analyses revealed an interesting relationship between DOA and automation failure detection, the "routine-failure tradeoff." The tradeoff suggests that when automation functions as it is supposed to, higher DOAs lead to better performance. However, when automation fails, the higher DOAs lead to poorer human-system performance. Further, there appears to be a DOA beyond which the negative effects of failure on performance become significant. This occurs because operators tend to reduce monitoring of reliable automation. When the DOA is high (such that operators play little direct role in the F/Ts automation is performing), the lack of monitoring leads to poor SA of automation's functioning. Therefore, when a failure occurs, it is difficult to detect and recover from.

Several researchers have suggested that one approach to managing this tradeoff is to refrain from using higher levels of automation; and there is empirical support for this approach. Intermediate and low DOAs support automation failure detection and management, especially when manual skills need to be preserved. This approach may also be favored by operators of real-world systems.

AA may provide an alternative approach because it provides operators with experience with various DOAs and that enhances the operator's understanding of how automation performs. AA may provide a means of including high DOAs when needed, but since lower DOAs are also used, operator performance is supported.

It was noted that other factors contribute to automation failure management including task sharing, HSI design, and training.

Most of the research discussed in this section focused on automation failures. Automation degradations and loss of functionality may be more difficult to detect. This situation was not addressed in the studies reviewed but warrants additional research.

5.3.3 Potential Challenges of Adaptive Automation

The conclusion stated above was that AA has the potential to address some of the challenges of human interaction with automatic systems. However, it also presents new issues to be addressed and they are summarized here.

Even when operators anticipate a configuration change, the change can interrupt their ongoing task performance. Configuration changes also can increase the workload associated with human-automation interaction, especially when changes are initiated by operators. These issues are worse when AA shifts configuration unexpectedly or when it should not. This can occur if the configuration changes result from triggers other than those initiated by operator command. It is important for configuration changes to be gracefully implemented to support seamless shifting of responsibilities between human and automation agents.

Another challenge is ensuring that operators know the implications of configuration changes for their roles and responsibilities. Not knowing these responsibilities presents the opportunity for a new type of error like “mode” errors.

Finally, when configuration shifts are initiated by assessments of OFS, there may be technological challenges and limitations to detecting and interpreting such states, such as the availability of sensors to accurately and reliably assess operator workload.

5.3.4 Generalizing the Research Findings

In prior research studies, the generalizability of the findings to real-world operational systems was considered (e.g., O’Hara, Higgins, & Pena, 2012). Research findings are generalized most easily when they closely match the target’s operational context. Dimensions to consider in the generalization process are listed in Table 5-2.

Often the systems, tasks, and HSIs used in research studies are simplified representations of real-world systems. In many of the AA studies reviewed, the systems were desktop and micro-simulations of actual systems such as ATC and UVs. These systems are greatly simplified when compared with the real-world systems they represent. Consequently, the tasks are simplified as well. Since the system is not represented in its full complexity, the task set participants need to perform is greatly limited and simplified. In addition, the HSI provided to interact with the system lacks the complexity of actual HSIs because only limited functionality is needed.

In many of the studies, the participants were relatively inexperienced non-professionals with limited training. Professional operators and naïve participants differ in their cognitive approaches to task performance and decision-making. In support of generalization, research findings ultimately should be confirmed with professionals in real-world settings (de Greef, Arciszewski, & Neerincx, 2010; Zsambok & Klein, 1999).

Table 5-2 Generalization of the Studies Reviewed

Generalization Dimension	Target Operational Context	Typical Study Reviewed
Application Domain	Nuclear power plants	The domains varied and included UV, ATC, and vehicles. The simulated systems usually were very simple and did not involve the complexity of real-world operations.
Functions and Tasks	Normal plant operations and emergency management	Simplified versions of the types of tasks the system domain demanded
System Representation	Various plant designs, such as pressurized water reactors	Simplified systems from the study domain, (e.g., simplified UV represented on a desk-top computer)
HSIs	Alarm, displays, and controls in control rooms designed to accommodate a crew of operators	Very simple, lacking the complexity and functionality of the HSIs in a typical control room
Personnel	Highly-trained, professional operators organized into a crew and supported by a wide variety of professionals, such as maintenance, engineering, training, etc.	While some professionals participated in these studies, most research used students with very limited experience and training

The results must be interpreted with these differences in mind. Future systems are in the early design phase where research can be directed to identifying issues and developing approaches and concepts for addressing them. Studies like those reviewed provide important contributions at this stage. Once identified, promising technologies and strategies to achieving AA's long-term goals can advance to the systems development and evaluation phase, where real-world mission constraints can be addressed.

6 HUMAN-AUTOMATION INTERACTION AND HSIs

6.1 Human-Automation Teamwork

O'Hara and Higgins (2010) emphasized recent perspectives of humans and automation working as a multi-agent team (Christoffersen & Woods, 2002; Hollnagel & Woods, 2005; Woods & Hollnagel, 2006). In a multi-agent team, human and machine agents work cooperatively to accomplish plant safety and production goals (Figure 6-1). Any activity in the plant, whether performed by human or automation agents, is accomplished by four generic primary tasks: monitoring/detection, SA, response planning, and response implementation. Automation can be applied to interface management tasks as well. If a human performs all the primary tasks, the F/T is said to be a manual F/T. If the automation performs them, the F/T is fully automatic. If the human performs some of the tasks and automation performs others, the F/T is at an intermediate level of automation. Humans and automation can also support these tasks when they do not perform them completely, such as a decision-making aid.

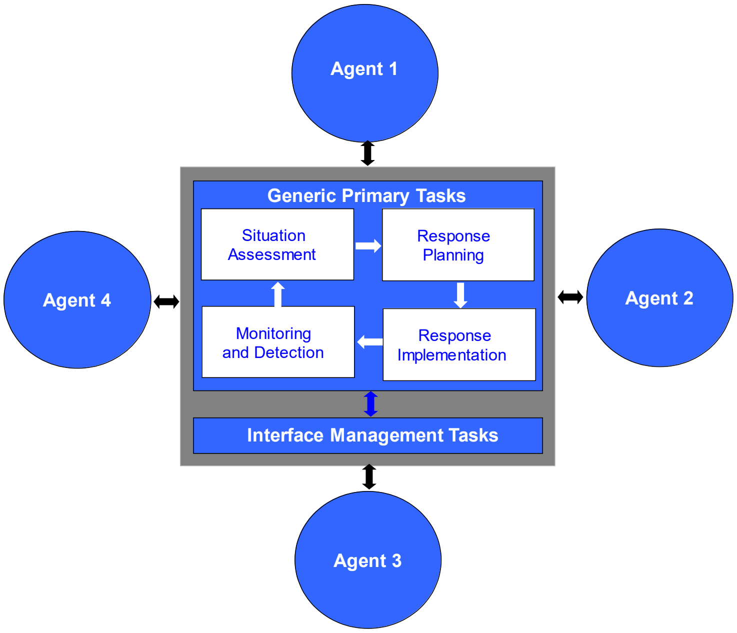

Figure 6-1 Multi-agents system monitoring and controlling the plant

Beyond competent and reliable task performance, what characteristics does automation need to possess to function as an effective teammate? Most of the research on designing automation to be a good "team player" has been based on an implicit notion of what it means to be a team player and how members of a team should perform to function successfully. The concepts employed, such as trust, are based loosely on a sense of what is important to human teamwork. That is, the assumption is that automation will be a good teammate when it behaves like a human teammate. In part, this makes sense because research has shown that humans relate to automation in similar ways to the way they relate to human teammates (Lee & See, 2004; Madhavan & Wiegmann, 2007). However, there are challenges with this approach. Specifically, what model of teamwork is appropriate to human-automation teams and how do we account for differences between human and automation agents.

First, if we want to model human-automation teams on the characteristics of human teams, what model of teamwork should be used? There is currently no consensus as to what factors are necessary to promote good and effective human teams (Salas, Cooke & Rosen, 2008). In fact, there may not be one appropriate model since what constitutes a good team may differ based on the overall mission of the team and of the individual characteristics of the members of the team.

Even if the focus is restricted to NPP crews, the issue of consensus on key characteristics of good teams still exists. Nuclear plant operations are accomplished through teamwork; the coordinated activity of multi-person teams. Operators share information and perform their tasks in a coordinated fashion to maintain safe plant operation as well as to restore the plant to a safe state when process disturbances arise. Crew members may perform a task cooperatively from one location, such as the main control room, while in other cases a control room operator may have to coordinate tasks with personnel located remotely.

O'Connor et al. (2008) identified team skills necessary for NPP operations based on interviews with 38 crews at three different plants in the United Kingdom. The skills were grouped into five categories, each with several sub-elements (Table 6-1).

Table 6-1 Important NPP Teamwork Characteristics

Category	Element
Building situation awareness	Develop understanding
	Anticipation
	Maintain overview
	Performance monitoring
Team focused decision making	Analytical decision making
	Procedure following
	Intuitive decision making
	Initiative
Communication	Assertiveness
	Information exchange
Co-ordination	Adaptability
	Supporting behavior
	Team workload management
Collaboration	Leadership
	Co-operation
	Followership

Note: Source is O'Connor et al. (2008)

Based on simulator observations, O'Hara and Roth (2005) identified a similar, yet broader set of factors important to NPP crew teamwork, including:

- having common and coordinated goals
- maintaining shared situation awareness
- engaging in open communication
- planning cooperatively
- monitoring the status of other team members
- backing each other up
- identifying errors proactively

Carvalho and colleagues identified somewhat different factors, including plant culture (Carvalho, dos Santos & Vidal, 2006; Carvalho, Vidal & de Carvalho, 2007). They performed field studies of NPP crews, and their analyses showed that communication was key in developing a shared understanding of the situation among the crewmembers (i.e., shared cognition), such that the correct decisions and courses of action could be taken. They showed that numerous cultural factors, including the leadership style of the senior reactor operator and the plant's safety culture can affect communication and the process of forming a shared understanding, which other research has shown is key to effective team coordination (Mathieu, Heffner, Goodwin, Salas, & Cannon-Bowers, 2000).

Park, Jung, and Yang (2012) also studied how characteristics of communication among NPP crews during simulated emergencies affected crew performance. Specifically, they found that the following communication characteristics improved overall crew performance during simulated emergency scenarios:

- a tightly coupled communication structure (e.g., which is an indicator of good team cohesion)
- increasing the amount/density of communication to increase team SA (e.g., crew members speaking up when observing changes in the system state)
- increasing the thoroughness of communication to make shared understanding more explicit (e.g., greater adherence to three-way communication practices)

Gertman, Haney, Jenkins, and Blackman (1985) found that the emotional stability of individual crewmembers' personalities was related to their future performance. Itoh, Yoshimura, Ohtsuka, and Matsuda (1990) showed that the cognitive abilities of perceptual speed and memory are also related to individual NPP crewmember performance, and as a result, overall team performance. Similarly, many studies show that group cohesion or lack thereof, can have an effect on team performance (Evans & Dion, 1991).

Three primary antecedent factors have been found to contribute to variability in performance between teams (Toquam et al., 1997):

- task characteristics (e.g., how routine and simple versus unusual and complex is the task the team must perform)
- team member characteristics (e.g., intelligence, personality types, and specific cognitive abilities)
- team dynamics (e.g., group cohesion and communication practices)

Further, the characteristics necessary to create good teams may differ based on the control room technology with which they interact. Chung, Yoon, and Min (2009) argued that communication protocols will vary depending on whether the crew is operating in a conventional control room or a computer-based control room. Similarly, Roth and O'Hara (2002) found that the introduction of computer-based aids into a conventional control room changed crew member roles and responsibilities and team processes.

The bottom line is that defining the key characteristics of human-automation teams based on those identified for good human teams may be premature as a consensus on an appropriate model is yet to emerge.

Another challenge with modeling human-automation teams is how to account for differences between human and automation agents. Research on how automation should behave (or designed to behave) to be a team player has not been based on the recognition that there are some fundamental differences between human behavior and how automation can be programmed to behave. Automation agents are not humans and are not likely to fully behave as a human member of a team. For example, automation agents cannot assume responsibility. Automation can be given the authority to act, but humans always maintain responsibility (Pritchett, 2001; Sarter & Woods, 1992). Pritchett and colleagues identified ways in which automation agents are different from human agents (Feigh & Pritchett; 2014; Kim, 2011; Pritchett, Kim, & Feigh, 2014 a & b):

- *Behavior when outside boundary conditions* – Human team members will continue to attempt effective performance in unfamiliar circumstances, while automation generally cannot.
- *Anticipating the needs of a teammate* – Good teammates anticipate each other's information needs and provide information. Automation is limited in this capability.
- *Managing interruptions* – Humans time their interactions based on the current situation, (e.g., another teammate's workload). Automation can be "clumsy" in this regard and interrupt human teammates at inopportune times.
- *Responsibility* – Automation does not have motivation and a sense of responsibility.

The design of automation teammates should address these differences.

Therefore, there are some technical obstacles to defining a comprehensive model of human-automation teamwork, including the lack of a consensus on the factors characterizing successful human teams and a need for a better understanding of the differences between human and automation agents.

6.2 HSIs for AA Interaction and Management

6.2.1 Supporting Situation Awareness and Managing Workload

Within the context of automation, supporting SA means supporting operator awareness of:

- the high-level status of automation's functioning
- detailed information about automation's current processes

O'Hara and Higgins (2010) discussed the design of HSIs for general human-automation interaction. While there are some unique considerations when considering AA HSIs, the general principles apply to AA HSIs, as well. It will be briefly summarized before turning to the unique characteristics of AA HSIs.

Many automation researchers have endorsed the use of displays based on ecological-interface design (EID) principles[10] for the rapid monitoring and understanding of automation's current status, especially for non-routine and failure conditions (e.g., Onnasch, Wickens, Li & Manzey,

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[10] EID refers to an approach to display design that focuses on presenting information at various "levels of abstraction" (from lower-level parameter information about a component to high-level plant functions such as critical safety function status). EID principles seek to display this information to making maximum use of graphical features to present information. See O'Hara, Higgins, & Kramer, 2000) for more information.

2014; Sheridan & Parasuraman, 2005). The use of EID displays for automation is summarized for the process of developing such displays in two phases: (1) conduct work-domain analysis to identify information requirements and (2) use the principles of EID to design information displays to present the required information to operators (Vicente, 1999; Burns & Hajdukiewicz, 2004).

- *Information requirements analysis* – Identifying the information operators need to interact with automation using (1) work-domain analysis using an abstraction hierarchy to identify the information needed to interact with automation and ecological interface design principles to increase the operator's understanding of automation and current situation awareness (Duez & Jamieson, 2006; Linegang et al., 2006); and (2) functional modeling using a means-end hierarchical structure (Liu, Nakata & Furuta, 2004; Piccini, 2002; Pirus 2004a & 2004b; Riera, 2001)
- *Detailed HSI design* – Presenting information about automation using ecological HSI designs, integrated displays, emergent features, and mixed modal feedback (Guerlain et al., 2002; Parasuraman et al., 1997, 2000)

EID HSIs provide for rapid processing by operators at low cognitive cost in part due to their simplicity and their use of visual graphics. The importance of HSI simplicity was supported by Mosier et al. (2012 &2013). Mosier et al. (2013) showed how design of the HSIs to automation impact pilot perception and use of flight management system (FMS) automation. Simple (e.g., one button changes) were found to have minimal negative impact on workload and SA as compared with HSIs requiring multiple inputs. Mosier et al. (2012) conducted a study with professional pilots who flew simulated scenarios using an FMS. The FMS had two different interfaces to accomplish flight management tasks: clumsy and easy. Also, varied were situational factors where unanticipated tasks had to be performed during some scenarios. The interfaces significantly affected workload and task management. With respect to SA, under routine situations, the HSI design did not affect SA, however, the clumsy HSI impaired SA when performing an unanticipated task.

While EID displays support high-level monitoring, operators also need access to more detailed information about automation processes. For example, one important aspect of automation that operators need access to is the basis for its decisions. Roth et al. (2004) evaluated the extent to which UAV operators understood the plans developed by automation when humans and automation cooperated as a team in the planning and execution of missions. They showed the need to communicate the rationale used by the automation and offer a means for operators to modify the automation's operations, without which operators cannot properly assess the appropriateness of automation's actions and whether changes are needed. Thus, HSIs should support automation-human communication so operators can determine and understand how the automation performs its tasks.

In AA systems, operators need to know the current configuration and when the configuration changes (i.e., configuration awareness) (Kaber & Kim, 2011). Configuration awareness is critical because each configuration shift is associated with new roles and responsibilities (Bindewald, Miller & Peterson, 2014).

The implication of loss of awareness of the current configuration is the potential for a type of mode error. That is, operators behaving as though one AA configuration is in effect when another configuration is actually active. Operator behavior appropriate for the mode they believe the automation is in may be inappropriate to the currently active configuration.

Silva and Hansman (2015) examined the mechanisms behind mode errors in crew interactions with flight management systems and suggested strategies to mitigate them. FMS mode errors are very similar to AA configuration awareness errors. Mode errors arise from a divergence between the systems actual mode and the operator's mental model as to what the current mode is. They identified three types of divergence (D):

- Type D-1: Automation shifts to a new mode, but the operator's mental model is not updated
- Type D-2: Automation does not shift to a new mode, but the operator's mental model is updated to reflect a new mode
- Type D-3: Automation shifts to a new mode, but the operator's mental model is updated to reflect a different new mode

The authors propose mitigation strategies to address the different types of divergences. Divergence Type D-1 can be addressed with salient feedback in the HSI as to the current mode. Type D-2 can be addressed through training and crosscheck procedures that include verifications of the currently active mode. For Type D-3, a combination of HSI feedback and crosscheck may be effective. These strategies should support AA operators to maintain awareness of the current AA configuration.

Parasuraman, Miller, and colleagues have proposed an HSI approach, the delegation interface, to support both configuration awareness and managing the workload of AA interaction (Miller & Funk, 2001; Miller & Parasuraman, 2007). Sheridan and Parasuraman (2005) discussed the importance of users maintaining control over adaptive systems. They note the issue of potential lack of predictability in adaptive systems and loss of SA, especially when configuration shifts are not under user control. In a team environment, a second issue is the potential for one member of the team to change the configuration while the other members of the team are unaware of the change. When users control the shifts, these issues are lessened. They acknowledge the potential of increased workload when users control configuration shifts. The challenge is to design an interface to minimize the workload associated with user control.

The delegation interface seeks to achieve the goals of ensuring awareness of the responsibilities of each agent while minimizing the workload associated with operator interactions with automation. The approach is modeled on work delegation in human teams. Delegation is the process of assigning specific roles and responsibilities for tasks for which the delegating agent retains authority and responsibility. As supervisory controllers, operators select tasks for automation to perform, and set procedures for how it must accomplish them. Communication between agents is expressed in terms of goals, methods, constraints, and resource utilization. The underlying concept is that operators can delegate *predefined* tasks to automation, thereby giving them a flexible approach to completing tasks and an efficient means of changing the DOA.

"Playbook" is one form of delegation interface. The name is based on the metaphor of a sports team's use of a "playbook," (i.e., a set of specific plays that all team members understand). The plays, based on a hierarchal task-model, reflect the system's DOAs. Groups of predefined tasks are organized into plays, with the relevant task parameters identified (specified when operators call a particular play), such as times and locations, thereby establishing a common understanding for all team members of what each individual agent will do. Operators can make real-time adjustments, but more effort is involved in communicating with the automation. However, this capability enables the "play" to be better tailored to a specific situation.

Playbook contains a planning function to develop a specific plan for a current situation. The planner has access to information, such as resources available (e.g., fuel), and can adjust the tasks accordingly. It alerts the operator about any constraints that would compromise success. Finally, if necessary, an event-handling function makes fine adjustments during the execution of the plans.

There is empirical support for the Playbook-delegation interface (Calhoun et al., 2013; Miller & Funk, 2001; Miller & Parasuraman, 2003, 2007; Miller et al., 2005; Miller, et al., 2011; Parasuraman, Galster, Squire, Furukawa, & Miller, 2005). In one study, Parasuraman, Galster, Squire, Furukawa, and Miller (2005) compared the effect of Playbook on the performance of UV tasks with a restricted interface with only one level of control. The success rate and time to completion were better with Playbook, although the benefits fell as the number of vehicles simultaneously controlled increased. The HSIs enabled operators to identify goals and instruct automation agents. Also, they adapted better and responded to the automation's ineffective behavior.

Calhoun et. al (2013) conducted a usability evaluation of a delegation interface for single operator adaptive control of multiple UAVs. The interface enabled operators to shift between four DOAs with manual control at the lower end and high-level command with automation controlling the vehicle at the high end. Participants included both pilot and non-pilots. They used the interface to control the UAVs in a desktop simulation. The data collected consisted of user comments collected during a think-aloud procedure used during the scenarios, as well as via a questionnaire and debriefings. The interface was rated highly and was considered easy to use. Recommendations for improvement were obtained and included the need for more flexibility in working with the different DOAs (e.g., using voice, touch, and mouse inputs). Many additional suggestions were made which are specific to the details of the HSI.

The lessons-learned from these studies is that providing operators with "set plays," (i.e., predetermined definitions of a set of roles and responsibilities of human and automation) helps support configuration awareness by establishing clearly defined roles and helps reduce the operator's workload in interacting with the automation since plays can be selected rather than having to be developed in real time. Note that while the delegation interface was developed for operator commanded AA, the general principles can be applied to other triggers as well.

6.2.2 Etiquette and Managing Interruptions

Communication is commonly identified as an important process factor in human teams. As automation becomes more interactive and more like a "team player," it is increasingly becoming an important factor in human-automation interaction as well. Miller (2015) observed:

> I think it is becoming increasingly clear that we need machines that are designed with an eye to how humans will perceive and interact with them on a social level, as well as computational models of those social interactions. After all, we are social beings and all our interactions with other "autonomous agents" (be they human or not) are necessarily social interactions. Failing to fully design for those interactions means we get random, and most likely undesirable, interactions as a result.

Identifying approaches for accomplishing this goal is a relatively new area of research.

Communications from automation can be disruptive and negatively impact task performance and workload (Maere et al., 2010). When prompts come too quickly, they add to workload and degrade performance. When they are not frequent enough, again, the operator's performance is negatively impacted because they do not get the necessary information. Maere et al. (2010) showed that one simple means of handling such disruptions is allowing operators to control the rate of automation prompts to help mitigate these effects.

Another means is to design the interactions between automation and its human teammates to follow rules of "etiquette." In the context of automation, etiquette means communications from automation that are "non-interruptive" and "patient." (Parasuraman & Miller, 2004). However, it is important for an automation system to know when it is appropriate to interrupt. Dorneich et al. (2012) gave the example that while it is inappropriate to interrupt a pilot during landing with a baseball score; it is appropriate to interrupt with the information that the landing gear has malfunctioned. Designing an automation system to communicate in a manner that follows social conventions of human teammates is a challenge because it requires knowledge of operator states and situations.

Dorneich et al. (2012) examined the role of operator workload as input to an AA system designed to manage interruptions. Participants performed simulated platoon scenarios involving five tasks: route navigation, keeping count of the number of civilians and soldiers sighted, maneuver monitoring, maintaining awareness of the overall situation, and a secondary math interruption task. During the scenarios, messages were received from a variety of sources such as unit commanders, soldiers, and others. The task load associated with managing the messages was varied from low (about 3 messages per minute) to high (about 8 message per minute). An adaptive communication scheduler was available during half the scenarios. When the participant's workload was high, the scheduler sorted messages such that only high priority messages were put through the communications equipment. Lower priority messages were sent as text messages to a personal computer. The system minimized interruptions during high workload periods. When the participant's workload was low, the scheduler did not sort the messages. The system determined the participant's workload based on EEG and ECG measurements. In the other half of the scenarios, no adaptive support for managing communications was available. Measures of the participant's task performance were obtained. The results showed that the scheduler improved task performance on priority tasks. At the same time, SA of the lower-priority task was lower. This tradeoff was considered acceptable, since the scheduler enabled participants to maintain awareness of the more important information.

Miller and Funk (2001) described the effort to design the etiquette of the U.S. Air Force's Rotorcraft Pilot's Associate (RPA). To do so they first studied the teamwork of helicopter pilots. The concept was that if the adaptive system was to be a teammate in the cockpit, it should emulate the etiquette of the crew. They observed that crews spend about one third of the time in "meta-communication" activities. These include communications such as those related to plans and intentions, allocations and affirmation of responsibilities, and maintenance of situation awareness. To emulate this behavior in the adaptive system, Miller and Funk developed the "Crew Coordination and Task Awareness" display to communicate "what the associate thought was going on." The display had four buttons to provide information to the crew pertaining to:

- the associate's current inference about the general, high-level mission context (e.g., currently engaged in an attack task rather than an evade task),
- the associate's inference about the highest priority current pilot task
- the task which the associate is engaged in currently which it believes has the highest priority

- the highest priority, inferred copilot task

If the crew felt something was wrong in the system's information in any of these areas, they could correct it.

Four flight crews (eight pilots) evaluated the system during realistic scenarios in a high-fidelity flight simulator. Half were flown with the display and the other half without. Following the scenarios, the pilots were given questionnaires to assess the system and the NASA TLX to assess workload. Pilot evaluations of the system were very favorable (e.g., most evaluated the display "Of Considerable Use" or "Extremely Useful"). They also rated their workload lower when the system was available. They did not, however, rate their overall performance higher with the system. Overall the authors concluded the effort to design the etiquette of the RPA by modeling its behavior on the meta-communications of human crews to be successful.

Based on their experience, Miller and Funk developed 12 'Etiquette Rules' for adaptive automation, stated from the perspective of the automation system:

1. Make many, many correct interaction moves for every error made
2. Make it very, very easy to override and correct your errors
3. Know when you are wrong, the easiest way to do this is to let the human tell you, and then get out of the way.
4. Don't make the same mistake twice
5. Don't show off, just because you can do something, doesn't mean you should.
6. Be able to talk explicitly about what you're doing and why. Humans spend a lot of time in meta-communication activities facilitating coordination, especially in distributed work environments.
7. Be able to take instruction; not only will this help you adapt to the user's expectations, it may actually make you look smarter.
8. Make use of multiple modalities and information channels redundantly; understand the implications of your communications on all the levels on which it operates.
9. Don't assume every user is the same, be sensitive and adapt to individual, cultural, social, contextual differences
10. Be aware of what the user knows, especially if s/he knows it because you recently conveyed it (i.e., don't repeat yourself).
11. Try not to interrupt. There may be times when something you want to convey is important enough to warrant interruption, but this will usually not be the case. Err on the side of caution.
12. Be cute only to the extent that it furthers your interaction goals.

The importance of designing AA systems with etiquette is even greater in high workload situations (Sheridan & Parasuraman, 2005).

In addition to managing disruptions and interruptions, etiquette has been found to help calibrate operator trust in automation (Atkinson et al., 2012).

6.3 Adaptive HSIs

In the discussion of Figure 6.1, it was noted that agents can support primary tasks and interface management tasks. In a computer-based control room, secondary tasks include activities such as navigating through or accessing information at workstations and arranging information on the screen. In part, these tasks are necessary because operators view only a small amount of information at any one time through the workstation displays. Therefore, they must undertake interface management tasks to retrieve and arrange the information. Interface management tasks are necessary to perform the operator's primary tasks.

The distinction between primary and interface management tasks is important because the latter created workload and may divert attention away from primary tasks and disrupt performance (O'Hara & Brown, 2002). Aspects of interface management are candidates for automation. Adaptive user interfaces can lower workload by automatically providing information relevant to the current operational context. Reducing the workload associated with interface management should provide more cognitive resources to devote to primary tasks. The design challenge is doing so while users can remain in control and have a full understanding of what is being presented to them (Roberts & Parush, 2007).

The communication scheduler system (Dorneich et al., 2012) discussed is an example of an adaptive HSI. Another very simple example is automating the alarm reset when many alarms are coming into the control room (Yenn et al., 2006). Another example of an adaptive HSI is the automatic identification of a display appropriate to the ongoing situation (e.g., identifying an emergency procedure display upon detecting any of the procedure's entry conditions). Here, the HSI would notify the operator of the availability of the display, such as via a blinking icon at the bottom of the screen, rather than disrupting the operator's ongoing activity by obtrusively showing the display. This type of automation may reduce the possibility of operators erroneously retrieving the wrong display.

Hou, Kobierski, and Brown (2007) developed an intelligent adaptive interface (IAI) that selects a display based on current situational factors involving mission changes and operator states like the triggering conditions discussed earlier. They investigated the efficacy of IAIs in a multi-UAV mission. The IAI was modeled as part of the UAV tactical workstations in maritime patrol aircraft. They used a performance model to compare the difference in mission activities with and without IAI agents. A prototype IAI experimental environment was implemented for a human-in-the-loop empirical investigation. Both the simulation and the experiments showed that, although multiple UAV control is a cognitively complex task, IAIs significantly reduced workload and improved SA, allowing operators to work under time pressure.

6.4 Conclusions

Various aspects of human-automation interaction were considered. The efforts to model human-automation teamwork were first examined. The research to define the key characteristics of human-automation teams has generally been based on modeling multi-agent teams after good human teams. However, a consensus has yet to emerge as to what constitutes good human teams, thus generalizing such models to multi-agent teams has had limited success. In addition, a robust model of human-automation teams must account for differences between human and automation agents. Therefore, most of the research to define how automation should be designed to behave to be a team player has not been based on a recognition that there are some fundamental differences between human and automation teammates.

HSIs bridge the gap between human agents and automation agents. A key consideration in designing AA HSIs is to support SA of the high-level status of automation's functioning as well as the detailed information about automation's current processes. Research has defined promising strategies to supporting SA using EID displays and detailed displays that are based on a comprehensive information requirements analysis. For AA HSI, an important aspect of SA is configuration awareness. Since configurations define operator and automation roles and responsibilities, lack of configuration awareness can lead to errors. The research on FMS mode errors since it is very similar to configuration awareness were examined. Recommendations for supporting configuration awareness were identified.

Another key consideration is the management of workload, especially for AA systems. Promising approaches to both support configuration awareness and also managing workload can be found in the research on delegation interfaces.

Etiquette is an important aspect of human-automation interaction for managing interruptions and distractions stemming from interactive automation. A promising approach to understanding etiquette requirements in an operational domain may be used to model its behavior based on how human teams interact. Such efforts are not as ambitious as developing a comprehensive human-automation teamwork model. Instead, they focus on a more limited set of behaviors in a specific application domain. Future successes in establishing models of human-automation teams should lead to advances in defining the etiquette requirements for human-automation interaction.

Finally, adaptive HSIs represent a means of supporting operators by performing interface management tasks. Such tasks potentially take cognitive resources away from primary tasks and can have a negative effect on performance. Adaptive HSIs have been found to lower this kind of workload.

7 HFE GUIDANCE FOR DESIGNING AND EVALUATING AA SYSTEMS

HFE standards and guidelines (S&Gs) documents play an important role in the design and evaluation of complex systems (Karwowski, 2006). S&Gs provide users with principles to help ensure that the physiological, cognitive, and social characteristics of personnel are accommodated in system development. They also support standardization and consistency of HSI characteristics and functionality. Many HFE S&Gs are developed by professional organizations such as the Human Factors and Ergonomics Society (HFES) and the Institute of Electrical and Electronics Engineers (IEEE) using a consensus process. Consensus S&Gs are periodically updated to keep current with new research and technological developments. Government organizations also develop HFE S&Gs. The Department of Defense's HFE Technical Advisory Group (DoD, 2004) listed over 30 U.S. government HFE standards. Like consensus documents, government S&Gs are periodically updated.

In this section, the HFE guidance that is available to support the design and evaluation of AA systems is discussed. It is organized around three topics:

- function allocation
- AA design and review
- evaluation and validation

7.1 Guidance on Function Allocation

O'Hara, Higgins and Pena (2012) identified two automation-related issues. One issue was "function allocation methodology to support automation decisions" which addressed the fact that function allocation methodologies have not kept pace with automation technology. There is a need for improvements in the methods available to designers for making automation decisions and the safety reviewers of those decisions.

7.1.1 General Function Allocation Guidance

Methods for the allocation of functions to humans and machines originated in the development of military systems. One of the first approaches was to allocate F/Ts to humans or automation using a Fitts list (Table 7-1). The analyst first evaluates F/Ts in terms of what abilities are needed for successful performance. The list is then consulted, and the F/T allocated to the most capable agent. Fitts lists are simple to use and require little training. Employing the technique requires only the Fitts list and a list of system F/Ts.

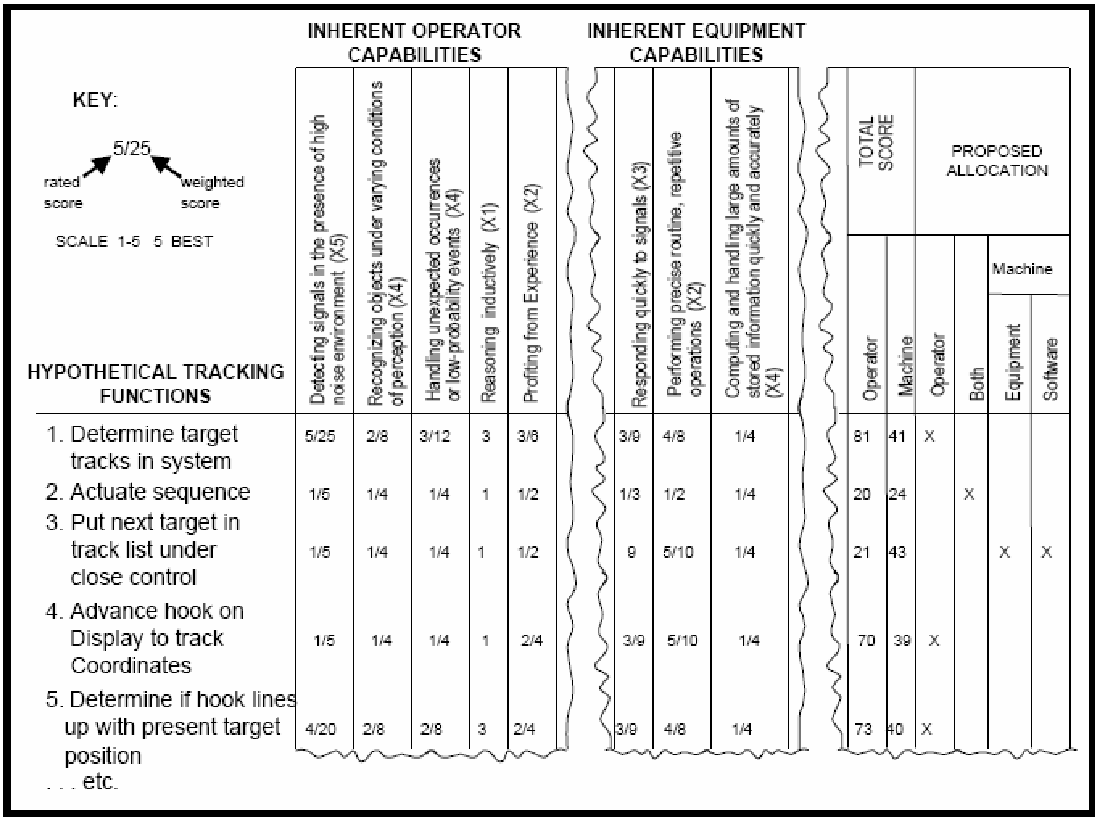
Table 7-1 Example of a Fitts List Comparing Human and Machine Capabilities

People Excel In These Activities	Machines Excel In These Activities
Detection of certain forms of very low energy levels	Monitoring (both people and machines)
Sensitivity to an extremely wide variety of stimuli	Performing routine, repetitive, or very precise operations
Perceiving patterns and making generalizations about them	Responding very quickly to control signals
Ability to store large amounts of information for long periods – and recalling relevant facts at appropriate moments	Storing and recalling large amounts of information in short time-periods
Ability to exercise judgment where events cannot be completely defined	Performing complex and rapid computations with high accuracy
Improvising and adopting flexible procedures	Sensitivity to stimuli beyond the range of human sensitivity (infrared, radio waves)
Ability to react to unexpected low-probability events	Doing many different things at one time
Applying originality in solving problems, (i.e., alternative solutions)	Exerting large amounts of force smoothly and precisely
Ability to profit from experience and alter course of action	Insensitivity to extraneous factors
Ability to perform fine manipulations, especially where misalignment appears unexpected	Ability to repeat operations very rapidly, continuously, and precisely the same way over a long period
Ability to continue to perform when overloaded	Operating in environments which are hostile to man or beyond human tolerance
Ability to reason inductively	Deductive processes

Note: Source is DoD, 1999

One criticism of the approach is that in actual system design, decisions about allocations are often iterative, rather than one-time allocations as suggested by the Fitts list approach. Another criticism is that the approach is overly simplistic in terms of human roles and uses qualitative terms only. Further, the capabilities of humans and machines are not always directly comparable; they can be complementary (Madni, 1988). That is, some F/Ts are better performed by both humans and automation (rather that humans or automation) since the FT demands require capabilities of both agents. This is one of the misleading aspects of applying a Fitts approach, it fosters a view that allocation is the process of substituting automation for human performance. However, allocation is not a simple substitution, rather the allocation process fundamentally changes human roles in the system and the F/Ts they will perform (Hollnagel, 1999; Thurman et al., 1977). The result of a Fitts list approach to allocation can be that the role of the humans in the system is ill-defined and both human and integrated system performance suffers. Its “either-or” process does not support AA decisions since AA fundamentally is based on a dynamic changing of allocations between human and automation agents.

Despite these criticisms, Fitts lists continue to be widely used and improved to accommodate technological advances (de Winter & Dodou, 2014). An example is the Function Allocation Evaluation Matrix (DoD, 1999). This technique is an extension of the Fitts' list approach that recognizes that some F/Ts may be best allocated to both human and automation agents. Like the Fitts list, F/T requirements are compared to the capabilities of hardware, software, and humans. A worksheet is used to document the evaluation (Figure 7-1). F/Ts are listed on the left side of the worksheet. The Fitts-like evaluation criteria are listed in the columns. The analyst can assign numerical weightings to the criteria. For example, the weightings can be defined by SMEs based on their importance to the F/T being analyzed. The scores are then entered in the table and summed for the “operator” and the “machine” allocations. The scores are used to make function allocation decisions. When the score totals are close to each other, then the allocation is made to “both” operator and machine. Once the allocation decision is to share the F/T, a further analysis must be made to determine if the shared F/T should be statically or dynamically implemented.



KEY:
5/25
rated score
weighted score
SCALE 1-5 5 BEST

HYPOTHETICAL TRACKING FUNCTIONS	INHERENT OPERATOR CAPABILITIES					INHERENT EQUIPMENT CAPABILITIES			TOTAL SCORE		PROPOSED ALLOCATION			
													Machine	
	Detecting signals in the presence of high noise environment (X5)	Recognizing objects under varying conditions of perception (X4)	Handling unexpected occurrences or low-probability events (X4)	Reasoning inductively (X1)	Profiting from Experience (X2)	Responding quickly to signals (X3)	Performing precise routine, repetitive operations (X2)	Computing and handling large amounts of stored information quickly and accurately (X4)	Operator	Machine	Operator	Both	Equipment	Software
1. Determine target tracks in system	5/25	2/8	3/12	3	3/6	3/9	4/8	1/4	81	41	X			
2. Actuate sequence	1/5	1/4	1/4	1	1/2	1/3	1/2	1/4	20	24		X		
3. Put next target in track list under close control	1/5	1/4	1/4	1	1/2	9	5/10	1/4	21	43			X	X
4. Advance hook on Display to track Coordinates	1/5	1/4	1/4	1	2/4	3/9	5/10	1/4	70	39	X			
5. Determine if hook lines up with present target position	4/20	2/8	2/8	3	2/4	3/9	4/8	1/4	73	40	X			
. . . etc.														

Figure 7-1 Example of a function allocation evaluation matrix
(Note: Source is DoD, 1999)

Allocation of functions methods have been included in a standard developed by the International Standards Organization (ISO, 2000). The standard describes the considerations to be used to allocate functions. An input to the allocation process is a set of F/Ts and their performance requirements. Preliminary allocations are made based on legal requirements, if any, which make certain allocations mandatory. Then allocations are based on the relative capabilities of human and machine agents, in a manner like a Fitts list approach. The allocation is further informed by prior experience with the allocations of similar F/Ts in previous systems. Additional considerations are included to address some of the challenges of automated systems, such as the need to maintain situation awareness and to maintain manual skills if human backup of automation is required. The standard further considers the integration of allocations to humans such that their role results in “challenging, interesting and satisfying jobs.” The ISO process includes the evaluation of allocations and their reallocation as necessary.

The standard acknowledges that not all F/Ts should be allocated in a fixed manner. Rather, some can be implemented in a dynamic manner based on situational workload. However, while dynamic allocation is acknowledged as an alternative to static allocation, the methodology does not clearly address how the analyst would identify when this alternative is preferred.

Bindewald, Miller, and Peterson (2014) proposed the use of a function-to-task design process for identifying aspects of functions to be adaptively performed. The overall process is based on a functional decomposition approach, much like hierarchal decomposition method of task analysis. Once functions are broken down into basic tasks, the tasks are allocated to agents to perform them. At this point the process depends on mapping tasks to the capabilities of the agents to identify those best suited to perform the task. After those tasks are identified for which the allocations are fairly clear, a set of tasks remain that can be performed by either agent. These tasks can be allocated dynamically, that is, the tasks can be allocated to human or automation agents based on human workload.

Bindewald et al., did not discuss the option of using a shared control approach, where these tasks are statically allocated to human and automation agents based on criteria other than agent capability. For example, a designer might assign a set of such tasks that are related to each other to automation when the tasks support a lower-level function while assigning a set of related tasks to the human operator when they support a higher-level function when the latter may support the operator to maintain overall situation awareness of system state.

Binderwald and colleagues provide a methodology that includes AA considerations as an option in the allocation process. However, it does not provide criteria, beyond the fact that the tasks are within the capability of both agents, to support the identification of when AA should be selected.

Therefore, the general FA guidance has advanced to the point of acknowledging AA as a viable allocation option, but the methodology has not been sufficiently developed to provide detailed processes to support the decision.

7.1.2 Nuclear Industry Guidance for Function Allocation

The NRC conducted one of the first studies in the nuclear industry on function allocation methodology. The objective of the study was to “develop criteria for assessing design proposals and concepts of automation that employ computer-based operational aids.” Price (1982) described the relationship between human and automation performance as a continuum that has many possible combinations, as is illustrated in Figure 7-2. The two-dimensional space is divided into "regions" indicating the best choice for allocation to automation or human performance:

- In Region 1, human performance is good and automation performance is poor, thus the F/T should be allocated to humans.
- In Region 2, human performance is good and exceeds automation performance, thus human performance is preferred.
- In Region 3, automation performance is good and human performance is poor, thus the F/T should be allocated to automation.
- In Region 4, automation performance is good and exceeds human performance, thus automation is preferred.
- In Region 5, there is little difference in the relative advantages of human and automation, thus the F/T can be allocated based on other criteria.

- In Region 6, neither human nor automation can be performed acceptably, thus the F/T should be redesigned.

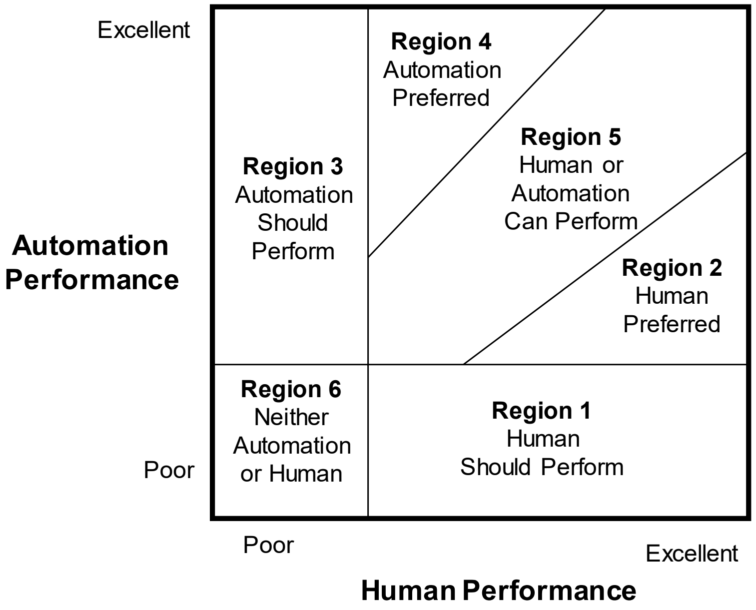


Figure 7-2 Relative combinations of human and automation performance
(Adapted from Price et al., 1985)

Pulliam et al. (1982) used the results of Price's work to develop a methodology for allocating nuclear plant control functions to human and automatic control. The methodology begins with the identification of functions to be allocated and steps through a decision flow chart until the functions are allocated to the regions depicted in Figure 7-2. The considerations include whether allocation to humans or automation is mandatory and whether performance by humans or automation is feasible.

While Region 5 allocations may be suitable to AA, the methodology is based on the assumption that F/Ts in this region will be statically allocated to humans or automation. Price et al. did not explicitly discuss the possibility of dynamic allocation. It is worth examining the method because the analysis that results in an assignment to Region 5 can include important considerations for AA. However, the methodology bins F/Ts into Region 5 at the end of the process when they have not been assigned to another region first. At that point in the process, F/T performance by either automation or humans is reasonable. Unfortunately, no considerations for selecting AA are presented.

Guidance for allocation of NPP functions is provided in the International Electrotechnical Commission's (IEC) standard on NPP control room design, IEC 60964 (IEC, 2009). Section 6 discusses the functional design of the control room, which is divided into functional analysis, function assignment, verification of function assignment, validation of function assignment, and job analysis. Function assignment is the allocation of functions. The standard requires the designer to develop and document criteria for function assignment based on the capabilities and limitations for human and automatic agents (much like a Fitts List approach). The guidance is high-level, and IEC 60964 refers the user to IEC 61839 (IEC, 2000) for more detailed guidance on assignment of functions.

IEC 61839 provides detailed guidance for functional analysis and assignment for nuclear plant design. The standard requires criteria to be developed for function assignment. These criteria may be based on:

- the requirements for accomplishing functions (i.e., time, complexity, and accuracy that are derived from functional analysis)
- national law, rules, and guidelines
- utility and vendor practices
- cost

The criteria should reflect the basic capabilities of human and automation agents. Following a consideration of legal requirements and utility practices, the process is much like a Fitts List approach where function requirements are matched to agent capabilities.

The allocation options include F/Ts that should be shared, but no actual guidance is provided for selecting this option. No reference is made to the adaptive implementation of shared F/Ts.

The standard notes that the process is iterative and should be validated (per the higher-level standard IEC 60964).

Guidance has been developed by the Electric Power Research Institute (EPRI) (Hanes, Fink, & Naser, 2015). The characterization of automation is based largely on the NRC's automation dimensions (O'Hara & Higgins, 2010). One dimension is "Allocation Flexibility," where static and dynamic allocation are both presented as design options. The allocation process uses a flow chart approach where decision points represent F/T characteristics important to the selection of humans, automation, or both. The F/T characteristics include considerations such as whether the F/T is a safety function, whether operators can perform the F/T, and whether automation of the F/T is technically and economically feasible. For all but fully automatic and manual F/Ts, the last decision in the process is whether the selected levels of automation are static or dynamic. Unfortunately, no specific guidance is identified in this conference paper on how this selection is made. The guidance has been incorporated into an EPRI guideline (EPRI, 2015).

The guidance available to NPP designers and reviewers is at a stage of development like that of the general FA guidance: AA is identified as an option in recent methods, but detailed processes for addressing AA are still lacking.

7.2 Guidance on AA Design and Review

7.2.1 High-Level Principles

Parasuraman, Barnes, and Cosenzo (2007) proposed the following principles:

1. Information displays should adapt to the changing military environment. For example, information presentation format (e.g., text vs. graphics) can change depending on whether a soldier is seated in a vehicle or is dismounted and using a tablet controller.

2. Software should be developed that allows the operator to allocate automation under specified conditions before the mission.

3. At least initially, adaptive systems should be evaluated that do not take decision authority away from the operator. This can be accomplished in two ways: (a) an advisory asking permission to invoke automation, or (b) an advisory that alerts the operator that the automation will be invoked unless overridden.

4. For safety or crew protection situations, specific tactical or safety responses can be invoked without crew permission.

These reflect conservative extrapolations of principles from the general literature. While they are made in the context of military systems, these principles can be applied to NPPs as well as other complex systems. The first principle recommends adaptive interface management, a feature that is already employed in existing designs. The second principle recommends a delegation style interface design. Delegation interfaces have been supported in the literature. The third principle recommends operator commanded triggers. Given some of the technical issues to implementing system-initiated triggers in operational environments, this recommendation seems reasonable, at least at the present time. The fourth principle is one already implemented in many systems, including NPPs.

Parasuraman et al. further recommend the evaluation of design options in a realistic environment before final design decisions are made.

Steinhauser et al. (2009) proposed a set of high-level design principles for AA systems. These principles are listed below (Steinhauser et al., 2009, p. 9):

1. Adaptive function allocation to the operator should be used intermittently. Intermittent allocation can improve performance in monitoring tasks.

2. Energetic human qualities should be considered in design. For example, degrees of challenge can be automatically adjusted with artificial tasks.

3. Emotional requirements of the human operator must be considered. The human operator should not feel unnecessary to the system as a whole.

4. The system should be calibrated to the individual operating it. Individual differences factor into the human operator portion of a human-system pairing and thus should be incorporated into the design.

5. Task transformation should be used to simplify tasks for operators. A task that is partitioned and transformed can be handled piecemeal instead of as a whole.

6. The environmental context of the system should be used to determine allocation. Environmental stressors such as heat, vibration, and gravitational force affect human performance and should be addressed.

7. Tasks should be partitioned when both the human and the system can contribute effectively. A true human-system collaboration operates as a pairing instead of a dichotomy of effort. Performance is improved when the most effective attributes of each part are employed.

8. Adaptation should be controlled by the system but be open to human intervention when the system fails to recognize new conditions or demands. In order to reduce task load on

the human operator and improve general performance, the system should allocate tasks. To improve satisfaction and motivation, the human operator should retain control, or perceived control, of the system.

With the exceptions noted below, these are high-level principles that are generally supported in this review. The second principle recommends the use of artificial tasks to adjust workload levels. The research that supports this suggestion is not known for this review. In the context of AA, workload can be adjusted using operational tasks. Alternatively, operators have other tasks they typically need to perform that are unrelated to AA and these can be used if their workload needs to be adjusted.

The eighth principle, that adaptation should be controlled by the system, may not be fully achievable at the present time. While the ability of system triggers is a goal of considerable AA research, there are still technical challenges to achieving this goal in actual operational environments. For example, using physiological parameters to monitor OFS is promising, but recording these parameters in a control room environment with active operators may be difficult. Then integrating the parameters to get reliable OFS results is still a research question. Further, considerable support does exist for operator demanded changes in AA configurations, and it is unclear why system induced triggering is preferred. This principle also is inconsistent with Parasuraman’s third principle listed above.

7.2.2 Detailed Guidelines

NRC

This section will examine the AA guidance available in existing NRC review guidelines. In a separate report (O’Hara, 2017), the suitability of that guidance for conducting a comprehensive review of AA systems is evaluated. The automation guidance in O’Hara and Higgins (2010) was reviewed by NRC users and revised accordingly (O’Hara, 2015). The new guidance on automation systems has been integrated into Revision 3 of NUREG-0700 (O'Hara & Fleger, 2020). The guidelines for reviewing the HSIs to automation are organized into subsections, as shown in Table 7-2.

Table 7-2 Organizational Structure of HSI Review Guidance for Automation Systems

9 Automation Systems

- 9.1 Automation Displays
- 9.2 Alerts, Notifications, and Status Indications
- 9.3 Interaction and Control
- 9.4 Automation Modes
- 9.5 Automation Levels
  - 9.5.1 Shared Control
  - 9.5.2 Operation by Consent
  - 9.5.3 Operation by Exception
- 9.6 Adaptive Automation
- 9.7 Computerized Operator Support Systems
- 9.8 HSI Integration

Section 9 includes design review guidance for AA. The guidance is shown in Table 7-3.

Table 7-3 NRC HFE Guidance for the Review of Adaptive Automation

9.6-1 Predefined Roles and Responsibilities
Adaptive automation should use predefined definitions of the roles and responsibilities of human and machine agents.
Additional Information: This will minimize the workload caused by changing the automation configuration and will support the operator's understanding of automation by limiting the number of available options.[67653]

9.6-2 Operator Control of Automation Shifts
The HSI should provide controls for implementing changes in automation.[67653]

9.6-3 Notification of Impending Changes to Automation
If automation can change for reasons other than by the user's request, the operators should be notified of the impending change with adequate time to override the change, if necessary.
Additional Information: Operators should be alerted to impending changes in automation (approach to triggering condition) so they are not surprised and have time to block or override it, if appropriate.[67653]

9.6-4 Identification of Triggering Conditions
If automation can change for reasons other than by the user's request, the triggering conditions and how automation has changed should be identified.
Additional Information: Adaptive changes can be made based on factors such as measured workload indicators, performance decrements, or other criteria.[67653]

9.6-5 Shift Confirmation of Automation Change
The HSI should confirm that a change in automation has taken place.
Additional Information: Adaptive changes should be confirmed positively by the system to prevent operators becoming confused about their current roles and responsibilities. [67653]

O'Hara and Higgins (2010) also contained design process and training guidance for automation systems. This guidance was also reviewed by NRC users and modified to address their comments. It has been included in Appendix B of NUREG-0700, Rev 3. Note that Appendix B of NUREG-0700 contains guidance for selected HSI topics (information displays, user interface interaction and management, and computer-based procedure systems) that address important considerations in the design of those topics.[11] The guidelines in the main sections of NUREG-0700 address the physical and functional characteristics of HSIs and not the unique design process considerations that may be important. However, in the development of guidelines, guidance developers often identify aspects of the design process or training that are important to consider. Since such considerations are not within the scope of the main design review guidelines, they are contained in NUREG-0700 Appendix B. For example, in the development of design review guidelines for automation, training emerged as a very significant factor in supporting reliable human-automation interaction. The considerations contained in Appendix B can be addressed by NRC reviewers on a case-by-case basis during specific reviews. The new process guidance for automation is organized into the sections shown in Table 7-4.

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[11] Note that this differs from the more general process review guidance in NUREG-0711. NUREG-0711 does not cover design considerations for specific HSI technologies.

Table 7-4 NRC HFE Guidance for the Review of the Adaptive Automation Design Process

Section B.4 Review Guidance for the Automation System Design Process

B.4.1 Operating Experience Review
B.4.2 Functional Requirements Analysis and Function Allocation
B.4.3 Treatment of Important Human Actions
B.4.4 Human-System Interface Design
B.4.5 Procedure Development
B.4.6 Human Factors Verification and Validation
B.4.6 Training Program Development

Federal Aviation Administration

The FAA's main HFE document is the *Human Factors Design Standard* (HFDS) (Ahlstrom et al., 2003). FAA HFDS, Section 3.13 contains nine guidelines on adaptive automation (see Table 7-5).

Table 7-5 FAA HFE Guidance for the Design of Adaptive Automation

1. Automation should be designed to adapt by providing the most help during times of highest user workload, and somewhat less help during times of lowest workload.
2. Adaptive automation should not be implemented unexpectedly or at a time when the user may not desire the aiding.
3. Adaptive automation should be implemented at the point at which the user ignores a critical amount of information.
4. Adaptive automation should be used to increase the performance of users with different skill levels.
5. Adaptive automation should be at least as skilled as the user, if not greater, to promote optimal user performance.
6. Modeling of human behavior for aid-initiated intervention should at least include: task execution goal states, environment representation (graphical), situation assessment information and planning, and commitment logic.
7. When dynamic adaptation of the interface is used, it should be attained by utilizing information provided to the system through user interactions within a specific context.
8. When dynamic adaptation of menus is used, the resultant menus should offer only the options that are relevant to the current environment.
9. Direct manipulation interfaces should be used to minimize the impact of a transition to manual control.

These guidelines address the use of AA for both task performance as well as interface management. They address some of the concerns about AA, such as the unexpected change in configurations. Guideline 6 identifies information needed for operators to monitor automation changes triggered by the system. Interestingly, guideline 5 addresses automation's competence, a factor we noted as important in human-automation teaming. The basis for guideline 9 is not completely clear. However, direct manipulation interfaces are thought to require less workload than alternatives, and it can be expected that such an approach to interface design will make the transition to manual control easier.

National Aeronautics and Space Administration

NASA-STD-3001 (NASA, 2007), the primary HFE guidance for the design of space vehicles, contains one guideline applicable to AA. Guideline 10.6.1.6, Automation Level Status Indication, states:

> Operators of automated and robotic systems shall be provided with information on the status of the automation, including when the system changes between levels of automation. Rationale: The intent of this requirement is to ensure that operators are always able to ascertain the status of automated processes to maintain mode awareness. The operators need to be able to determine and affect what level of automation the system is operating in, as well as which processes are being automated. Analysis will determine cases where alerting may be required when automation takes control from human operators or switches to a higher level of automation.

This guideline addresses the issue of operator awareness of system-initiated changes in AA configurations and is essentially the same as NUREG-0700's guideline 9.6-3.

Department of Defense

DoD's *Design Criteria Standard: Human Engineering* (MIL-STD-1472) is primarily used in the acquisition of DoD systems (DOD, 2012). It includes one requirement addressing AA. Requirement 5.12.3.1.1, item g, states that the automated system shall provide a means for changing the allocation of roles and responsibilities between human and other system components. However, no additional guidance is provided.

In summary, some guidance for the design and evaluation of AA systems is available in HFE S&G documents, but it is limited. Some of the key AA design considerations are not yet addressed, such as:

- How to determine the number of configurations operators can manage before the design of the AA system becomes overly complex. Also, distinguishing between configurations and the relative roles and responsibilities associated with each before it becomes difficult
- How should invoking thresholds be established
- What is the minimal time configuration that should be in effect to establish system stability from the operator's perspective?

7.3 Guidance for the Evaluation and Validation of AA Systems

The need to evaluate the functions allocated to human and machine agents is identified in many HFE standards and guidance documents (e.g., IEC 90964) (IEC, 2009), as discussed in Section 7.1. For example, NUREG-0711's, "Functional Requirements Analysis and Function Allocation Review, Criterion 8" states that the applicant should verify that the allocation of functions to humans and automatic systems assures a role for personnel that takes advantage of human strengths and avoids human limitations. However, these documents do not specify how the evaluation should be made. Instead, function allocation evaluation is considered as part of the general HFE evaluation.

The same is generally true of the detailed AA design (i.e., general HFE evaluation and validation methods can be applied). Parasaurman et al. (2007) recommended the evaluation of AA design in a realistic setting before implementation, but no specific methodology is provided. However, several authors have addressed some of the unique considerations of automation and AA.

Oglesby et al. (2014) proposed a general approach to the evaluation of automation focusing on performance measurement. Measures are divided into three categories:

- input measures, including user inputs (personality and expertise), automation inputs (reliability, adaptability, and level of automation), and contextual inputs (team factors, task complexity, and the task environment)
- process and state measures, including attitudes (trust and complacency), behaviors (monitoring and automation use), and cognitive states (situation awareness, workload, and skill decay)
- outcome measures, including task time, errors, overall goal achievement

Many of the studies reviewed used performance measures in these categories. The value of such a framework is that it can lead to a more comprehensive and systematic approach to guide selection of measures to evaluate automation. It can provide standardization and help to ensure that important measures are not overlooked. For example, team measures are not often evaluated, but they should be, especially for AA systems that are often thought of as a team member, which can impact the roles, responsibilities, and communications of the human team members (O’Hara & Roth, 2005; Roth & O'Hara, 2002).

Cahill and Callari (2015) proposed a “safety case” approach to validation of AA systems. The methodology was developed as part of a research program on AA in the aviation domain. The overall objectives are to validate:

- the design of the cockpit as a co-operative system (i.e., pilot/automation coordination/ teamwork, distribution of task activity between the crew and automation)
- pilot comprehension of automation (i.e., status of automation, who is responsible for what task and what are they doing) and the avoidance of automation surprises
- how automation supports workload management and reduction of crew stress in high workload and potentially safety critical situations
- how the design supports crew briefing/planning, situation assessment, information management and decision making (i.e., Crew Resource Management[12] concepts)
- how the design supports error identification and recovery

As the validation process unfolds, a “safety case” is developed consisting of two parts: a theoretical framework and the specification of what information is needed to establish the case (i.e., how the adaptive automation concept and associated technologies will yield specific operational and safety benefits). The safety case is developed in four phases. Phase one addresses background concepts that underpin the safety framework. In Phase 2, the specific

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[12] See Helmreich and Foushee (1993) for a discussion of crew resource management concepts.

safety case for the design is articulated. Phase 3 addresses the design of the AA system. Phase 4 articulates the operational and safety benefits of the design.

The methodology itself is described in general terms rather than explicit step-by-step procedures. Validation begins early in a design project and is iteratively performed throughout the development of the AA system. Early evaluations address the evaluation of design requirements. Later evaluations address early design concepts implemented using low-fidelity prototypes. As the design matures, it is tested using scenarios performed on high-fidelity prototypes. A final evaluation of the overall integrated system is performed using realistic scenarios and high-fidelity simulation in order to show the overall safety and operational impact.

An interesting aspect of the process is that it is designed to obtain input from both internal and external stakeholders, thus providing diverse perspectives on what aspects of the design and operations need to be validated.

The approach proposed by Cahill and Callari includes some noteworthy characteristics. The first is its broad perspective, looking at validation from a broader perspective than design testing alone. The validation includes design process considerations, such as design requirements validation. Second, the process of validating across the design life cycle, beginning with initial design activities and culminating with integrated system validation of the final design. Third is the recognition of the need to build a safety case to support validation decisions. Fourth is the involvement of multiple stakeholders.

The approach is similar to current suggestions in the nuclear industry to view validation from a perspective beyond integrated system validation (ISV). One of the outcomes of the 2015 validation workshop sponsored by the Working Group on Human and Organizational Factors (WGHOF) of the Nuclear Energy Agency (NEA) was the importance of a phased approach to validation NEA/WGHOF (2017). A phased approach means that validation is an ongoing activity beginning early in the design process and is periodically addressed until integrated system validation is performed on the final design. Guidance to support a phased approach to validation is currently being developed by the IEEE.

Another parallel to the nuclear industry is in the use of “safety cases” to support validation conclusions. This was also discussed in the validation workshop (NEA/WGHOF, 2017). The logic underlying the safety case approach is that overall conclusions regarding the acceptability of the design is not simply based on data analysis. Conclusions involve making judgments about the overall results and the process upon which those results were obtained. Confidence in the ability to generalize the findings beyond the ISV to actual plant operations is essential for being confident in the results and the conclusions derived from them.

The most clearly articulated description of a safety case approach was made by Skraaning (Skraaning & Strand, 2015). They argue that the arrival at a validation conclusion requires an “acceptability analysis process.” The process is illustrated in Figure 7-3 (reproduced from their paper). They summarized this process, as follows:

> In the second stage of the acceptability analysis, the validation team compiles all the detailed ISV results and judge the overall acceptability of the new control room. This analysis includes findings for each crew and individual operator; each scenario and scenario type; and for every performance measure included in the validation. The validation team must weigh the importance of the detailed performance observations and search for meaningful results that can substantiate whether the new control room is acceptable. To

achieve this goal, it is necessary to reveal systematic effects, converging results, and other consistent patterns that are hidden in the huge and complex ISV data set. In addition, the relative importance of plant performance, task performance, team performance and cognitive performance for the operational safety should be clarified. We also have to interpret conflicting evidence and contra-intuitive results. Furthermore, the validation team has to take into consideration that some performance indicators may have more predictive value than others, i.e., some measures may express the acceptability of human performance only in the sampled scenarios, while other measures anticipate operator performance in future scenarios. The validation team needs to evaluate minimum performance as well as typical performance, i.e., focus both on the acceptability of the lowest observed performance scores and average performance scores. In addition, we have to consider the principal and practical weaknesses of the validation methodologies, such as benchmarking, operationalization of requirements or expert rating in the specific ISV. Generic methodological issues like simulator fidelity, scenario representativeness, participant training, statistical conclusion validity etc. should also be evaluated to estimate the trustworthiness of the findings in the particular validation study (see NUREG-0711 rev3, pp. 85-93). Finally, possible unanticipated adverse effects of the new control room design have to be taken into account.

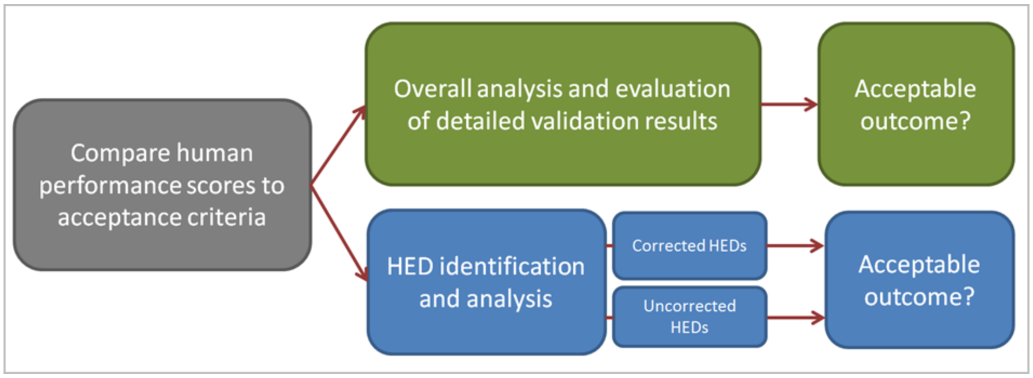

Figure 7-3 Acceptability analysis process

Skraaning and Strand, consider this process similar to building a safety case and reference a United Kingdom Office of Nuclear Regulation document (Office of Nuclear Regulation, 2013) that describes what a safety case should involve:

> A safety case should communicate a clear and comprehensive argument that a facility can be operated or that an activity can be undertaken safely. The safety case for a facility or activity should demonstrate that the associated risk and hazards have been assessed, appropriate limits and conditions have been defined, and adequate safety measures have been identified and put in place.

However, validation conclusions do not only pertain to safety. A parallel argument needs to be made for the production side of validation objectives.

The acceptability analysis process is a potentially valuable augmentation to the validation process, in general, and should be useful in the validation of AA systems.

An approach based on NUREG-0711's framework of integrated system validation and modified to incorporate automation specific considerations is proposed. Like the Oglesby et al. (2014)

approach, it has the advantages of a comprehensive and systematic approach to performance assessment.

A robust approach to performance measurement is generally considered important to system tests/evaluations (ANSI/AIAA, 2001; DoD, 2011, 2012; IEC, 1995; & ISO, 2010) and regulatory assessments (O'Hara et al., 2012). In part, due to the broad application of automation to all aspects of plant operations and maintenance, the studies of automation reviewed in this report illustrate the need for a comprehensive measurement approach, encompassing function and task accomplishment, cognitive performance, and teamwork. Table 7-6 summarizes the dimensions of performance characterization.

Table 7-6 Performance Measurement Framework for the Assessment of Human-Automation Interaction

Performance Dimension	**Example Measures**
Integrated System Performance	Function Performance
	Process Task Performance
Cognitive Task Performance	Monitoring and Detection
	Situation Awareness
	Response Planning
	Response Implementation
	Interface Management Task Performance
	Workload
Teamwork	Communication
	Trust

Two additional consideration are (1) the known human performance challenges associated with human-automation interaction, and (2) the type of plant operations embedded with AA. That is, the performance measurement approach should reflect the unique human performance challenges associated with plant operations. For example, within the context of SMRs, research on multi-unit operations has shown that measures such as "unit neglect" are important factors in multi-unit performance. Unit neglect is related to monitoring and SA.

Performance needs to be characterized by dimensions that encompass both integrated human-automation performance and by the aspects of personnel performance that mediate its usage.

Integrated System Performance

Function Performance

Automation and personnel work together in various ways to accomplish a mission, function, or purpose. The overall accomplishment of that function reflects the success of the human-automation collaboration. Therefore, measures of function accomplishment are ultimately the "bottom line" from an operations standpoint. Measures of function performance are scenario specific. While they are an important criterion for success, these measures are typically not diagnostic; that is, they do not provide an indication as to:

- whether successful function accomplishment was achieved in an undesirable way, such as with poor SA or high workload, that may bring into question the reliability of performance

- why function accomplishment failed

The performance dimensions discussed below provide information as to how performance was achieved (or failed).

Process Task Performance

Automation and personnel accomplish functions by performing tasks. Tasks include activities such as following procedures, responding to alarms, starting pumps, and aligning valves. The measures chosen to evaluate personnel task performance should reflect those aspects of the task that are important to system performance, such as:

- time
- accuracy
- frequency
- amount achieved or accomplished
- consumption or quantity used
- subjective reports of participants
- behavior categorization by observers

Cognitive Task Performance

While function and task performance are key aspects to the overall integrated system success, they do not typically provide sufficient information to ensure that reliable performance can be predicted under changing conditions or diagnostics when performing assessment of less than acceptable performance. The measurement of cognitive performance helps fill this gap.

Cognitive measures such as SA and workload are constructs that are essential to understanding and predicting human-system performance in complex systems, especially those employing extensive automation (Parasuraman, Sheridan, & Wickens, 2008). For example, Wickens et al. (2010) noted that SA was a critical factor in dealing with automation failure and tended to mitigate the poor handling of disturbances often associated with high levels of automation. They indicated that designers need to focus on increasing the operators’ SA for automation by finding its right level for tasks, improving the HSI for automation, and training.

Monitoring and Detection

A key aspect of performance, especially when unplanned events occur, is monitoring and detection. These measures are scenario specific and often tied to key events.

The monitoring of automation has been an issue in highly automated systems as has the detection of automation degradations and failures. Thus, including performance measures to assess these cognitive behaviors of operators is important in AA to better understand its effect on human performance.

An example of how measures should reflect the operational environment in which AA is embedded is the potential issue of “neglect time” (Crandall & Cummings, 2007) and “change detection” or “change blindness” (Parasuraman et al., 2009) in multi-modular SMR monitoring. The latter issue refers to the phenomenon of failing to see large, salient changes in the environment (Simons & Ambinder, 2005). These issues were identified in the automation of multi-unmanned vehicle operations yet may have applications to NPP SMR operations as well (O'Hara, Higgins, & Pena, 2012).

Situation Awareness

SA is the evaluation of current conditions to determine that they are acceptable or to determine the underlying causes of abnormalities when they occur (e.g., diagnosis). Like monitoring and detection, SA has been a long-recognized issue in automated systems.

There are many different methods to measure SA; however, they do not all measure the same aspect of SA and some may be better than others for evaluating SA related to human-automation interaction (Schuster et al., 2012).

Response Planning

Response planning refers to deciding upon a course of action to address the current situation. In general, response planning involves operators using their situation model to identify goal states and the transformations required to achieve them. Assessing the impact of AA on the ability of crews to develop response plans when needed should be included in evaluations and validations of AA systems.

Response Implementation

Response implementation refers to performing the actions specified by response planning. Measures of response implementation complete the primary task loop and provide for an assessment of HSI efficiency. Some response implementation activities are needed when interacting with AA systems and these should be included in the evaluation.

Interface Management Task Performance

To perform their primary tasks successfully, crews must successfully perform interface management tasks. As discussed earlier, these tasks create workload and may divert attention away from primary tasks and make them difficult to perform (O'Hara & Brown, 2002). Thus, secondary tasks are important and need to be carefully addressed in design reviews. This aspect of performance is important for AA system evaluations for two reasons. First, operator interactions with AA can create interface management tasks. Second, AA can be used to minimize these tasks through adaptive HSIs. Both aspects should be included in AA evaluations and validations.

Workload

Performing tasks produces workload. If workload is too low, vigilance suffers and the ability of personnel to develop accurate situation assessment diminishes. As the demands of performing the task rise, greater workload is experienced. Ultimately, if workload gets high enough, the ability to perform the task is reduced. Workload is a significant factor in addressing automation's effects. Automation can impose additional workload and, if high enough, may lead operators to abandon it (e.g., disuse of automation). Many approaches are available to measure workload (e.g., NASA TLX).

Teamwork

Many, if not most, of the activities performed by plant personnel require teamwork. That is, tasks are accomplished by the coordinated activity of multi-person teams. As automation increasingly fulfills its role in multi-agent teams, it impacts teamwork and needs to be assessed (O'Hara & Roth, 2005; Wright, 2002). As teams are social entities (Salas, Cooke & Rosen, 2008), integrating non-human team members has to be assessed. Many approaches to assessing teamwork have been developed (e.g., see Palmqvist, Bergström & Henriqson, 2012).

One important aspect of teamwork that plays an important role in personnel use of automation is "trust." The benefits of automation can be offset when operators do not trust it. If operators do not trust automation, they may not use it; of if they do, their workload may be significantly increased by overly verifying the automation's behavior. Similarly, failures of automation can remain undetected if operators trust it too much and hence, become complacent. Thus, constructs such as trust are important to assess as part of developing and evaluating a system. Measures of trust have been developed for this purpose. For example, Jian, Bisantz, and Drury (2000) developed the "System Trust Scale" which was validated by a factor analysis study (Spain, Bustamante & Bliss, 2008). The comprehensive performance measurement strategy needed to characterize performance also should reflect the unique aspects of human-automation interaction that are often found as important mediators to the operators use (and misuse) of automation. Trust is an example of one such measure. Many of the general measures listed above also can be tailored to focus on the operator's interaction with automation – such as SA, and workload.

7.4 Conclusions

Function Allocation

The review of current advances in FA methodology has not substantially changed the overall conclusion from the issue that there remains a need for improvements in the methods available to designers for making automation decisions, especially as they relate to AA.

Many HFE standards do not address FA methods (e.g., IEEE, 2004) and when they do, they rely heavily on methods that have Fitts lists at their core. While some of the limitations of such an approach are addressed in more current approaches, such as updating lists for technology improvements and recognizing the need for design iterations, they are still quite limited in addressing other important allocation considerations, such as the importance of maintaining situation awareness for human agents, the impact on workload as scenarios lead to a situation where operators are simultaneously responsible for multiple F/Ts, and the need to maintain skill proficiency for F/Ts that human agents will be expected to perform if automation fails.

More recent guidance has acknowledged AA has an option and alternative to static allocation, but little guidance is available to designers for selecting this alternative.

HFE Guidelines

Most of the general principles and guidance available are fairly high level. The NRC and FAA have provided perhaps the most detailed guidance currently available. While this guidance is mostly justified based on current research, it does not address important design and evaluation considerations for AA systems. Examples of these limitations include:

- How to determine the number of configurations operators can manage before the design of the AA system becomes overly complex. Also, distinguishing between configurations and the relative roles and responsibilities associated with each before it becomes difficult
- How should invoking thresholds be established
- What is the minimal time configuration that should be in effect to establish system stability from the operator's perspective?

Evaluation and Validation

The general HFE approaches to system evaluation and validation are appropriate to the evaluation of AA systems. As is generally the case, available approaches are improved when a systematic and thorough framework is used to guide the evaluation to help promote standardization and ensure that important factors are not overlooked.

As with any good evaluation, it should address unique design characteristics and known human performance issues. In the case of AA systems, unique design characteristics include consideration such as number of configurations, length of configurations, and the specific invoking thresholds established for the triggers. With respect to known human performance issues, measures such as operator trust in automation, skills decay, and automation failure management should also be included.

The safety case approach may represent a promising enhancement of AA evaluation and validation, but the approach needs additional applications in order to fully understand its contributions.

8 DISCUSSION

8.1 Lessons Learned from Current Research and Operations

The conclusions and lessons learned from this study are briefly summarized here. The reader is directed to the conclusion subsections within each section for a more detailed discussion. The material is organized into the following sections:

- Effects of Adaptive Automation on Performance
- Human-Automation Interaction and HSIs
- HFE Guidance for Designing and Evaluating AA Systems

8.1.1 Effects of Adaptive Automation on Performance

In general, AA supports improvements in task performance. Varying DOAs improves operator's understanding of how automation functions. There are exceptions; however, and it has to do with a mismatch of task demands and automation support in some studies. Matching automation support to task demands is an important consideration in the design of any automation system.

The effects of AA on SA and workload are complicated. Some studies did find improved SA while others did not. This result may be dependent of the specific nature of the tasks.

Some studies found lowered workload for AA systems, while others did not. This finding is in part due to what an AA system is compared with. If AA is compared to a manual condition, workload is likely to be lower. If AA is compared with a static automation condition, workload is likely to be higher.

Operators generally preferred operator commanded triggers. Operator commanded triggers keep the operator in control of the system and reduce potential surprises and distractions when a configuration shift occurs that the operator did not expect. However, operator commanded triggers can increase workload.

The other triggering categories, such as assessments of task performance, OFS, and task load, have also been used successfully and have minimal effect on workload. However, they have the potential to cause disorientation and distractions that can lead to transient performance decrements. Also, technical challenges have been noted for some OFS indicators, such as physiological parameters, including:

- the potential for physiological variables to change very rapidly
- integrating variables over time to get reasonable invoking thresholds
- interference and noise from other physical activity such as moving around
- uncertainty of its viability in the operational environment of a control room

Resolving these issues would be a significant advancement because it would provide an unobtrusive means of assessing OFS and can be used to increase automation in advance of performance decrements.

Hybrid approaches to triggering AA configuration changes has also shown promise and has the potential advantage of providing a more robust approach to determining when changes should be initiated.

For any triggering condition except operator command, an important decision is the identification of an appropriate invoking threshold; the specific point at which the trigger changes the AA configuration. The research reviewed provided little insight into the process of determining invoking thresholds.

Another important consideration in the design of AA systems is the number of configurations the system has, and the minimum time configurations should remain active. Unfortunately, the research provided few answers to these questions.

Deriving conclusions about the effect of AA on performance was sometimes hampered by experimental designs that did not provide a clean test of AA (e.g., it was sometimes not possible to determine whether performance differences were due to the adaptive characteristic of automation or simply due to providing automation support to operators). Future studies should ensure that their designs support the assessment of the hypotheses they are designed to test.

The support AA gave operators in the detection of automation failures and management of them were examined. However, very little research specifically addressed this question. The limited research reviewed tentatively supported the conclusion that it does.

While AA was shown to help address some of the challenges of human interaction with automatic systems, it also presents new issues:

- Configuration changes can interrupt an operator’s ongoing task performance and can increase the workload associated with human-automation interaction, especially when changes are initiated by operators. This issue is worse when AA shifts the configuration unexpectedly or shifts it when it should not.
- It is vital that operators know the implications of configuration changes for their roles and responsibilities. This is a key to AA’s success. Not knowing these responsibilities presents the opportunity for configuration awareness errors, a type of error like “mode” errors.

The issue of generalization of the findings of the review to real-world applications were discussed. Often the systems, tasks, and HSIs used in studies are simplified representations of real-world systems. The participants were relatively inexperienced non-professionals with limited training. In support of generalization, research findings ultimately should be confirmed with professional operators in real-world settings.

8.1.2 Human-Automation Interaction and HSIs

The research to define the key characteristics of human-automation teams has generally been based on modeling them after good human teams. However, a consensus has yet to emerge as to what constitutes good human teams, thus generalizing such models to multi-agent teams has had limited success. In addition, a robust model of human-automation teams must account for differences between human and automation agents. Additional research is needed to address these limitations.

HSIs bridge the gap between human agents and automation agents. Research has defined promising strategies to HSI design for AA systems:

- supporting SA using EID displays and detailed hierarchal displays
- supporting AA configuration awareness and workload management using delegation interfaces
- managing interruptions and distractions stemming from interactive automation by developing etiquette principles

Adaptive HSIs represent another approach to supporting operators by performing interface management tasks, thus minimizing the increased workload and distractions they cause.

8.1.3 HFE Guidance for Designing and Evaluating AA Systems

Function Allocation

There remains a need for improvement in the methods available to designers for making automation decisions, especially as they relate to AA. Many HFE standards do not address FA methods and when they do, they rely heavily on methods that have Fitts lists at their core. More recent guidance has acknowledged AA as an option and alternative to static allocation, but little guidance is available to designers for selecting this alternative.

HFE Guidelines

Most of the general principles and guidelines available are fairly high level and do not address important design and evaluation considerations for AA systems. For example, there is no guidance on:

- determining the number of configurations operators can manage before the design of the AA system becomes overly complex and distinguishing between configurations and the relative roles and responsibilities associated with each becomes difficult
- establishing invoking thresholds
- determining the minimal time a configuration should be in effect to establish system stability from the operator’s perspective

Evaluation and Validation

General HFE approaches to system evaluation and validation are appropriate to the evaluation of AA systems. Some considerations to enhance the evaluation include:

- using a systematic and thorough measurement framework to guide the evaluation to help promote standardization and ensure that important factors are not overlooked
- addressing the unique design characteristics and known human performance issues associated with the operations of the design
- addressing the human performance issues associated with automation such as operator trust in automation, skills decay, and automation failure management
- considering a safety case approach to support the development and justification of conclusions

8.2 Approaches to Improving Human-Automation Interaction

The review suggests several promising ways in which human-automation interaction may be improved. Approaches include:

- automate F/Ts based on a need for automation, not simply because they can be automated
- use appropriate degrees of automation for automated F/Ts, not simply very high levels by default
- introduce real-time flexibility in F/T allocation
- improve the human-automation interaction

Automate F/Ts Based on a Need for Automation, Not Simply Because They can be Automated

In the early 1980s when the ironies of automation were coming to light, the failure to address the operator's role in automated systems was implicated. Accordingly, Wiener and Curry (1980) noted, "the question today is not whether a function can be automated, but whether it should be." This question is still being asked today (Hancock, 2014), since the tendency to automate on technology grounds with little consideration of the operator's role persists.

Wiener's caution reminds designers and reviewers that both human and automation agents play important roles in system productivity and safety. When the design process focuses on one agent at the expense of the other, overall integrated system performance is likely to suffer. Further, there may be F/Ts that are better left to human operators, even though automation is technically possible.

Use Appropriate Degrees of Automation for Automated F/Ts, Not Simply Very High Levels by Default

Another approach to improving human-automation interaction is to use lower DOAs than can be technically accomplished. While such an approach is appropriate in some situations, overall it runs contrary to the designer's motivations to automate in the first place. However, research has shown that, in general, intermediate DOAs are better for higher-level generic tasks, such as situation awareness and response planning, while higher DOAs are suitable for "lower-level" generic tasks, such as monitoring and response execution. This general result has been supported when applied to computer-based procedure usage in NPPs as well (Lin, Yenn & Yang, 2010). AA may provide a greater opportunity to include high DOAs since operators are exposed to multiple DOA levels and that enhances their understanding of automation.

When using lower DOAs, the opportunity arises to make automation more interactive (i.e., human agents and automation agents interact to accomplish F/Ts). Following this approach, F/Ts are accomplished using varying DOAs. Some F/Ts are performed primarily by personnel with automation assisting. In other cases, F/Ts may be performed primarily by automation, with personnel performing other aspects of the F/T. This approach is consistent with recent perspectives of humans and automation working as a multi-agent team.

Introduce Real-Time Flexibility to F/T Allocation

F/Ts have historically been implemented in a static fashion (i.e., F/Ts are assigned either to automation, or humans, or some combination of agents, in an unchanging manner). Recent consideration has been given to AA, the dynamic allocation of F/Ts in response to the operator's current situation. For example, if the operator's workload gets too high, automation is increased to assume some of the operator's responsibilities and, therefore, lowers the operator's workload. When operator workload is low, the level of automation is decreased, and the operator assumes more control over tasks the automation was performing. Operator workload is thereby increased, reducing concerns for complacency and boredom. An additional benefit is that by assuming more direct control, the operator maintains manual skills proficiency (Parasuraman & Wickens, 2008). AA has the potential to address many of the issues associated with highly automated systems; hence it is receiving a lot of attention from designers and researchers.

Improve the Human-Automation Interaction

Human-automation interaction and HSI design in contributing to the performance issues associated with highly automated systems is important. Making automation more interactive and "cooperative" involves improving the communication between human and machine agents. Achieving this goal involves several design activities:

- designing the automation to enable interaction with operators, such as making relevant information available
- designing the HSIs to make it easier for operators to interact with automation (i.e., to monitor, query, configure, and control automation)
- designing automation's communications with operators to reflect principles of etiquette that are consistent with the operational domain so that they are less disruptive

Improving the interaction between humans and automation will help them to work more flexibly with each other.

8.3 Research and Development Needs

8.3.1 Key Enabling Technologies and Issues

The following topics require additional research:

Overall Impact of AA on Performance

The research on the effects of AA on performance, SA, workload, and failure management was reviewed. Generally, support for AA was found; however, the findings were not always consistent or were based on a limited number of studies. Additional research to better understand these effects are needed and to help resolve inconsistent findings. Future studies should be designed to more clearly pinpoint the unique effects of the adaptive aspects of AA rather than simply showing the benefits of automation. In addition, there are issues in generalizing from the findings of the research reviewed to their application in real-world systems with professional operators. More work is needed to test the generalizability of the conclusions to have confidence in them.

Function Allocation

O'Hara, Higgins & Pena (2012) identified the issue of *Function Allocation Methodology to Support Automation Decisions* (i.e., that available HFE methods do not adequately support the function allocation process). The evaluation of current advances in FA methodology has not substantially changed the overall conclusion. There remains a need for improvements in the methods available for making AA decisions. While more recent HFE guidance has acknowledged AA as an option and alternative to static allocation, little guidance is available to designers for selecting this alternative or to safety reviewers evaluating those decisions.

Configurations

While AA systems provide configurations offering operators different DOAs, the number of configurations that are appropriate and the minimum length of time the configurations should remain in effect before the configuration shifts become disruptive is not known. An additional area to be addressed is the potentially disruptive effects of configuration changes, especially when triggered by conditions other than operator command.

Triggers

While the triggering conditions used in the research studies reviewed were generally effective at switching AA configurations, more research is need on those using measures to assess OFS. OFS is often predicted using physiological measures. Researchers have used single physiological measures or multiple measures. A question remains as to which measures are best and how they should be integrated to get reliable OFS predictions. Further, some researchers recommend the use of hybrid triggers (i.e., the use of triggers from more than one category). A research question remains as to which ones provide the most reliable triggers and how they should be combined to trigger DOA changes. Finally, a key consideration is the invoking threshold (i.e., the specific point at which the trigger changes). Research is needed on determining these thresholds and on how to implement them, so configurations shift in an acceptable manner.

Teamwork

If automation is part of a multi-agent team, then what model of teamwork should be used to specify its characteristics? There is currently no answer to this question. Additional work is needed to identify appropriate teamwork models that incorporate an understanding of the differences between human and automation agents.

HSIs

HSIs provide the link between the operator and automation. The work on EID displays to support monitoring and failure detection and delegation interfaces to support configuration awareness and workload management was discussed. The work on automation etiquette to help make automation’s communication with its human teammates more acceptable and less disruptive was also discussed. While all this research is promising, much more needs to be done, especially because automation is becoming more interactive. In addition, the use of adaptive HSIs to support interface management and reduce the workload associated with it looks promising. Additional research is needed to identify applications within nuclear power plant operations and to ensure that automation’s performance of these tasks does not disrupt operator tasks or create confusion.

8.3.2 Need for Operational AA Systems

There have been few actual AA systems fielded in real-world operating systems. This limits the lessons that can be learned from the actual deployment of these systems with real operators. There is a need for additional demonstration systems that can prove the concept.

The availability of lessons learned from deployed systems will also support the assessment of generalizations from the type of research studies reviewed in this report. Most of the research on AA has been performed using simplified systems and non-professional participants. While the conclusions from these studies are suggestive, they need to be verified for generalizability to actual operations.

8.3.3 HFE Guidance for AA Implementation and Review

Despite the recognized importance of human-automation interaction, limited guidance is available to designers to implement systems supporting modern human-automation interaction and for regulators responsible for evaluating them. This situation is worse for AA when compared with static automation. Thus, additional work is needed to identify successful approaches and to develop design and review guidance supporting their implementation.

There was a discussion on the methods used to allocate functions to human and machine agents and their limitations within the context of static allocation. Methods are needed to help designers make decisions about the appropriate DOAs for F/T allocations, the use of flexible approaches to F/T allocations in real time, and the assessment of overall F/T allocations on operator roles to help ensure their roles are consistent with their capabilities and limitations, and are coherently integrated into a meaningful set of responsibilities. Better approaches will also help regulators to review the rationale for design decisions about how human and automation responsibilities are determined.

Another area is detailed HFE guidelines for AA. The guidance available from the NRC and other organizations were reviewed. While a limited set of guidelines is available, they do not address many important characteristics of AA.

8.4 Final Conclusions

The nuclear industry has recognized the need to provide more flexible automation to support operations. GE's PGCS and EdF's FITNESS are examples of the use of AA to support normal operations.[i] Both designs provide operators with flexible control over the DOA applied at any point in time and are operator commanded systems. Currently, new plant designers are developing AA systems for their plants. AA supports performance and may increase the crew's ability to detect and manage failures. In doing so, AA can help mitigate the well know human performance issues associated with highly automated plants.

As experience is gained with AA systems and as industry standards and guidelines increasingly identify AA as a function allocation option, it is likely that AA applications will become more widespread.

While AA can be applied to any aspect of plant operations, obvious candidates for adaptive approaches are operator support systems and HSIs. Computer-based normal and emergency procedures easily lend themselves to AA. Operators can select higher DOAs for times when they are busy and routine operations are being performed. They can select lower DOAs when a critical event is occurring, and they need to remain “in-the-loop” to ensure procedures are being conducted properly.

New, digital control rooms have hundreds or even thousands of displays. This can create a large interface management burden. Adaptive technology can assist operators in managing the HSIs and ensuing that the proper display is available. Interface management tasks increase workload and can interfere with the performance of primary tasks of monitoring and controlling the plant. Reducing interface management workload will help operators maintain focus on their primary tasks.

An additional consideration is the development of methods to assess OFS. While these methods are being developed to provide triggers to change configurations in AA systems, the ability for automation to monitor operator states is useful in its own right.

Operators are needed in most complex systems to handle unplanned and unanticipated events and to form the last line-of-defense in the face of automation degradations and system failures. The ability of crews to manage situations that are unforeseen is an important component to overall system resilience (Woods & Cook, 2006) and AA has been identified as an important technology to enhancing that resilience (Zieba et al., 2010).

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[i] The authors note that this was what the research indicated at the time. However, this information may not be current at the time of publication.