# EFFECTS OF ADAPTIVE AUTOMATION ON OPERATOR-SYSTEM PERFORMANCE

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## ABSTRACT

Adaptive automation (AA) is the dynamic, real-time change in the degree of automation in response to situational changes. AA systems are being developed in many industries, including for nuclear power plant applications. AA is a promising means of mitigating human performance issues that often arise in highly automated systems. The purpose of this Nuclear Regulatory Commission study was to characterize important AA design features, define the effects of AA on performance, examine the human factors engineering (HFE) guidance available to design and evaluate AA systems, and identify research and development needs. In general, we found that AA improves task performance and situation awareness (SA) while managing workload. Although the research is limited, AA also supports operator recognition of automation failure and recovery. Research on human-system interfaces has identified principles showing promise for supporting SA, including failure detection, and limiting workload. Research further suggests that AA systems are both more effective, and less disruptive and distracting, when they follow rules of interaction similar to those used by human crewmembers. Our general conclusion about the HFE guidance available to designers and reviewers is that it is limited and has not kept pace with automation technology. We discuss several research and development needs that will help support a better understanding of where and how AA should be used and support the development of more comprehensive guidance for AA safety reviews.

*Key Words*: automation, adaptive automation, human factors, regulatory review

## 1 INTRODUCTION

Adaptive automation (AA) is the dynamic, real-time change in the degree of automation (DOA) in response to situational changes. AA is a promising means of mitigating human performance issues that often arise in highly automated systems, such as loss of situation awareness (SA), complacency, and degradation of manual skills [1]. AA systems are being developed in many industries, including for nuclear power plant (NPP) applications [2]. Thus it is important to understand this emerging technology and its applications to nuclear plant operations and safety.

## 2 OBJECTIVES AND METHODOLOGY

The purpose of this Nuclear Regulatory Commission (NRC) study was to characterize important AA design features, define the effects of AA on performance, examine the human factors engineering (HFE) guidance available to design and evaluate AA systems, and identify research and development needs. To accomplish these objectives 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. This paper summarizes the results of the research; additional details can be found elsewhere [2].

# 3 RESULTS

## 3.1 AA System Characterization

Key characteristics of AA systems include configurations, triggering conditions, and human-system interfaces (HSIs).

### 3.1.1 Configurations

A configuration is a DOA that defines the roles and responsibilities of both operators and automation. AA configuration changes involve dynamic changes in automation dimensions, such as the level of automation. There are several decisions that are important to the design of configurations that have potential consequences for human performance; thus they are important to safety reviewers:

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?

### 3.1.2 Triggering Conditions

Triggers are the conditions that initiate changes in AA configurations. They include:

- Operator Command – A configuration change is made when commanded by the operator.
- Operator Functional State (OFS) – A configuration change is made when an OFS threshold is reached, e.g., high workload level, low SA, or fatigue. This class of triggers requires monitoring of operator state, e.g., through the use of 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.
- Event – A configuration change is made when specific events are detected.
- Hybrid – More than one type of triggers is used, such as when a configuration change is made when specific situations are detected. This is referred to as a hybrid trigger.

Important decisions for the design of triggers include:

1. Appropriateness of Trigger Categories - Which category of trigger or combination of categories is appropriate for the specific AA system?
2. Invoking Thresholds - What is the specific point at which the trigger should change the AA configuration?

### 3.1.3 Human-System Interfaces

HSIs provide the link between the operator and automation. HSIs are made up of the alarms, displays, controls, and communications necessary for operators to interact with the AA system. There are several decisions that are important to the design of HSIs:

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 effective and efficient communication between operators and automation fostered?

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 such as operator request, OFS, plant state, and key events. Figure 1 illustrates the relationship between configurations and triggers.

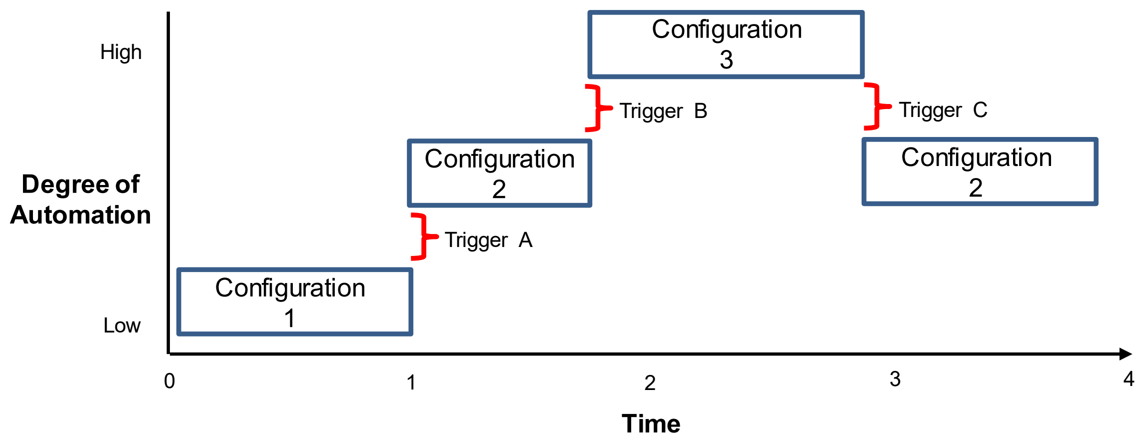


**Figure 1 Dynamic changes in automation over time**

## 3.2 Effects of Adaptive Automation on Performance

This section briefly summarizes the effects of adaptive automation on performance, specifically task performance, SA, workload, and detection/management of automation failures. Additional details and references to individual studies can be found elsewhere [2].

In general, AA supports improvements in task performance. Varying DOAs improves operator's understanding of how automation functions. However, there are exceptions; situations where varying the DOA does not improve performance. We think these have 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 task performance, OFS, and task load, also have 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 about its use in the operational environment of a control room

Resolution of these issues will be a significant advance because it will provide a fairly unobtrusive means of assessing OFS and can be used to increase automation in advance of performance decrements.

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

For any triggering condition, except operator commands, an important decision is the identification of an appropriate invoking threshold. 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 uses and the minimum length of time the configurations should remain active. Unfortunately, the research provided little information to address these questions.

We looked at the support AA gave operators in the detection of automation failures and management of them. However, very little research specifically addressed this question. The limited research reviewed tentatively supported the conclusion that it does improve failure detection/management performance.

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

- 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. When operators do not fully understand these responsibilities, the opportunity for configuration awareness errors arises; a type of error similar to "mode" errors.

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

- Supporting SA through the use of ecological design principles and detailed hierarchal displays (Ecological designs depict complex relationships through readily understood graphical designs)
- Supporting AA configuration awareness and workload management using delegation interfaces (delegation interfaces seeks to ensure awareness of the responsibilities of each agent while minimizing the workload associated with operator interactions with automation)
- Managing interruptions and distractions stemming from interactive automation by developing etiquette principles (etiquette means communications from automation that are "non-interruptive" and "patient' [3].

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

Formulating conclusions about the effect of AA on performance was hampered by a couple of considerations. First, some of the experimental designs did not provide clean tests of AA, e.g., it was not possible to determine whether performance differences were the result of the adaptive characteristic of automation or simply due to the fact that any automation was provided (adaptive or not).

Second, the issue of generalization of the findings to real-world applications must be considered.

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

## 3.3 HFE Guidance for Designing and Evaluating AA Systems

We evaluated the HFE guidance available to designers and reviewers in three areas: Function allocation, HSI guidelines, and evaluation and validation.

### 3.3.1 Function allocation

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 function allocation methods and when they do, they rely heavily on methods that have Fitts Lists at their core. 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.

### 3.3.2 HSI guidelines

Most of the general principles and guidelines available is fairly high level and does 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

### 3.3.3 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.

Thus, our general conclusion is that the HFE guidance available to designers and reviewers is limited and has not kept pace with automation technology.

## 3.4 Research and Development Needs

We identified the following research and development needs:

*Overall Impact of AA on Performance* – We generally found support for AA; however, the findings are not always consistent, based on a limited number of studies, or based on college student participants rather than professional operators. Additional research is needed to confirm the conclusions based on existing studies and to better understand AA's effects.

*Configurations* – Research is needed to define how many individual configurations are appropriate and the minimum time configurations should remain in effect before shifting them becomes disruptive.

*Triggers* – While the triggers evaluated were generally effective for switching configurations, additional work is needed to define effective measures of OFS, such as high workload. A key consideration is the invoking threshold; i.e., the specific point at which the trigger changes the configuration. Research is needed to determine how to define and implement them so that configurations shift in an acceptable manner.

*HSIs* –Since automation is becoming more interactive, additional research is needed to ensure that automation does not disrupt operator tasks or create confusion.

*HFE Guidance for AA Design and Review* - Additional work is needed to develop design and review guidance to support AA implementation and assure its design supports operator performance and safety.

*Teamwork* – While AA creates a multi-agent team, additional research is needed to identify an appropriate model of human-automation teamwork so that its desirable characteristics can be identified. The research conducted to define the key characteristics of human-automation teams has generally been based on models of 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 has to account for differences between human and automation agents. Additional research is needed to address these limitations.

# 4 DISCUSSION

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 [4] and AA has been identified as an important technology to enhance that resilience [5].

The nuclear industry has recognized the need to provide more flexible automaton to support operations. Currently, some 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-known 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.

AA can be applied to many aspects of plant operations including operator support systems and HSIs. For example, operators using computer-based normal and emergency procedures 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 [6]. Thus, reducing interface management workload will help operators maintain focus on their primary tasks.

# 5 REFERENCES


1. O'Hara, J, & Higgins, J. (2010). *Human-System Interfaces to Automatic Systems: Review Guidance and Technical Basis* (BNL Technical Report 91017-2010). Upton, NY: Brookhaven National Laboratory.

2. O'Hara, J. & Higgins, J. (2016). *Adaptive Automation: Current Status and Challenges* (Draft BNL Technical Report No. D0013-1-2016). Upton, NY: Brookhaven National Laboratory.

3. Parasuraman, R. & Miller, C. (2004). Trust and etiquette in high-criticality automated systems. *Communications of the ACM*, **47** (4), 51-55.

4. Woods, D. & Cook, R. (2006). Incidents - markers of resilience or brittleness? In E. Hollnagel, D. Woods, & N. Leveson (Eds). *Resilience Engineering: Concepts and Precepts*. Aldershot, UK: Ashgate.
5. Zieba, S., Polet, P., Vanderhaegen, F. & Debernard, S. (2010). Principles of adjustable autonomy: A framework for resilient human–machine cooperation. *Cognition Technology and Work*, ***12***, 193–203.
6. O'Hara, J. & Brown, W. (2002). *The Effects of Interface Management Tasks on Crew Performance and Safety in Complex, Computer-Based Systems*. (NUREG/CR-6690). Washington, D.C.: U.S. Nuclear Regulatory Commission.