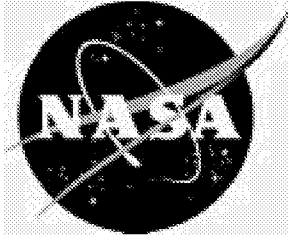NASA/TP-2002-211932

Workload-Matched Adaptive Automation Support of Air Traffic Controller Information Processing Stages

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September 2002

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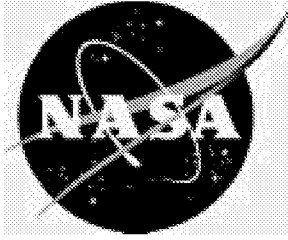
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Abstract

Adaptive automation (AA) has been explored as a solution to the problems associated with human-automation interaction in supervisory control environments. However, research has focused on the performance effects of dynamic control allocations of early stage sensory and information acquisition functions. The present research compares the effects of AA to the entire range of information processing stages of human operators, such as air traffic controllers. The results provide evidence that the effectiveness of AA is dependent on the stage of task performance (human-machine system information processing) that is flexibly automated. The results suggest that humans are better able to adapt to AA when applied to lower-level sensory and psychomotor functions, such as information acquisition and action implementation, as compared to AA applied to cognitive (analysis and decision-making) tasks. The results also provide support for the use of AA, as compared to completely manual control. These results are discussed in terms of implications for AA design for aviation.

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Acronyms

AA	Adaptive Automation
ATA	Air Transport Association of America
ATC	Air Traffic Control
DFA	Dynamic Function Allocation
SA	Situation Awareness
EDD	Electronic Data Displays
TPA	Trajectory Projection Aids
CDA	Conflict Detection Aids
CAA	Clearance Advisory Aid
EEG	Electroencephalogram
SD	Standard Deviation
LOA	Level of Automation
TLX	NASA Task Load Index
ANOVA	Analysis of Variance

Introduction

Automation refers to "... systems or methods in which many of the processes of production are automatically performed or controlled by autonomous machines or electronic devices" (Billings, 1997, p. 7). Billings stated that automation is a tool, or resource, that allows the user to perform some task that would be difficult or impossible to do without the help of machines. Therefore, automation can be conceptualized as a process of substituting some device or machine for a human activity (Parsons, 1985). The dramatic increase in technology has significantly impacted all aspects of our daily lives. The Industrial Revolution ushered in an era of untold innovation that has not only made life easier and safer, but has also provided much more leisure time. One need only imagine washing one's clothes on a washing board, something considered an innovation during the early 1900's, to see how automation has transformed how we see ourselves and our place in the world. Automation has become so pervasive that many devices and machines are not even considered by most people to be "automated" anymore. Others, such as the modern airplane, however, do not escape visibility so easily. Wiener and Curry (1980), and Wiener (1989) noted that avionics has provided not only a dramatic increase in airline capacity and productivity coupled with a decrease in manual workload and fatigue, but also more precise handling, relief from certain routine operations, and more economical use of airplanes. Unlike the washing machine, the increased automation in airplanes and air navigational systems, however, has not developed without costs.

The invention of the transistor in 1947 and the subsequent miniaturization of computer components have enabled widespread implementation of automation technology to almost all aspects of flight. The period since 1970 has witnessed an explosion in aviation automation technology. The result has been a significant decrease in the number of aviation incidents and accidents. However, there has also been an increase in the number of errors caused by human-automation interaction; in other words, those caused by "pilot error." In 1989, the Air Transport Association of America (ATA) established a task force to examine the impact of automation on aviation safety. The conclusion was that,

> "During the 1970s and early 1980s...the concept of automating as much as possible was considered appropriate. The expected benefits were a reduction in pilot workload and increased safety...Although many of these benefits have been realized, serious questions have arisen and incidents/accidents have occurred which question the underlying assumption that the maximum available automation is ALWAYS appropriate or that we understand how to design automated systems so that they are fully compatible with the capabilities and limitations of the humans in the system" (Billings, 1997 p. 4).

A need exists to reconsider the development of advanced automated systems in aviation that truly support human-centered design. A recent approach has been termed, "adaptive automation." However, although the concept of adaptive automation has been reported to have significant promise for mitigating "hazardous states of awareness" (Pope & Bogart, 1992) for flight crews (e.g., Haas, Nelson, Repperger, Bolia, & Zacharias, 2001; Prinzel, Freeman, Scerbo, Mikulka, & Pope, 2000; Prinzel, Pope, & Freeman, 2002; Scallen & Hancock, 2001), adaptive automation has not received a similar amount of research focus in other aerospace domains, such as air traffic control (ATC).

Automation for Aviation Systems

In considering aviation systems, including air traffic control (ATC) workstations and aircraft, the current role of automation is restricted by the limitations of expert systems (Leroux, 1993). In general, automation is not capable of higher-order cognitive functions, such as information integration and decision-making, which are required for effective performance in ATC operations and piloting tasks (Leroux, 1993). Humans must remain part of decision-making processes in the control of such systems in

order to ensure optimal performance. The key limitation of automation for ATC is the lack of expert system capability to consider the context of a decision and to quickly select an alternative, as humans often do on the basis of decision making heuristics and biases.

With these limitations in mind, some researchers (c.f., Laois & Giannacourou, 1995) have posed the question as to whether automation only should be applied to, for example, data acquisition and communication tasks versus it being applied to decision making functions or tasks requiring higher-order aspects of information processing. For example, Laois and Giannacourou (1995) stated that automation is generally better for monitoring tasks whereas humans are better at decision-making, especially in critical situations. That is, in the context of aviation system operations, automation is most suited to early sensory and information acquisition stages of information processing while humans are well suited to the latter (i.e., advanced stages of processing). They studied human performance in an ATC simulation and surveyed expert controllers to determine the implications of automation of ATC decision-making functions on performance. They observed significant performance decrements when futuristic forms of automation (conflict projection and clearance advisory) were applied to decision functions in the simulation, particularly when high-level automation was used. The survey results indicated that automation only should be applied to data acquisition and communication versus conflict projection and clearance advisory.

This past body of research suggests that caution should be exercised when considering the application of automation to ATC because of limitations in current technology and the implications of automation on human operator performance when applied to advanced functions, such as decision-making. The results found reported by Laois and Giannacourou (1995) demonstrate that automation of certain ATC functions may potentially undermine the overall objective of automation: To augment the Air Traffic Controller Operator skills.

Brief Review of Contemporary Adaptive Automation Research

Adaptive automation research has primarily focused on evaluation of performance and workload effects of dynamic allocations of control of early sensory and information acquisition functions as part of human-machine system operations. Kaber (1997), Kaber and Riley (1999) and Parasuraman et al. (2000) all reviewed a number of empirical studies of AA that have focused on the performance effects of Dynamic Function Allocation (DFA) in complex systems, specifically monitoring and psychomotor functions. On the basis of studies including Parasuraman (1993), Hilburn et al. (1993), Scallen et al. (1995) and Parasuraman et al. (1996), it is known that AA significantly improves monitoring and tracking task performance in multiple task scenarios, as compared to static automation and strictly manual control conditions.

Unfortunately, little work has been conducted to establish the impact of AA on cognitive function performance (e.g., decision-making) or to make comparisons of human-machine system performance when AA is applied to various information processing functions. The AA review literature has also pointed to the limited number of studies that have investigated the implications of DFA (a.k.a., adaptive automation) on cognitive task performance. As one example, Hilburn et al. (1997) conducted a study of AA in the context of ATC to examine whether decision-making automation could be used to reduce operator workload and optimize performance. Specifically, they evaluated the use of an automated Descent Advisor that calculated aircraft trajectories and dynamically developed flight plans. The tool detected planning conflicts, or projected separation conflicts, and offered the human operator advice to resolve conflicts. Experienced Air Traffic Controllers were required to control an airport arrival traffic simulation with or without the assistance of the automation. Hilburn et al. (1997) used three automation schemes including constant manual control, constant automation and the AA condition (under which the automation was invoked only during high traffic conditions to simulate workload relief). They found that the AA condition resulted in the smallest increase in mental workload across trials. This research provides some support for the use of automation and/or AA in cognitive/decision making tasks. However,

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additional research is needed to establish the relative effectiveness of AA applied to higher-order cognitive functions in comparison to AA of low-level sensory and information acquisition functions in specific contexts. This would provide additional insight into the utility of AA for addressing static automation problems across information processing functions.

Some work that has indirectly investigated the implications of AA of lower-order aspects of human-machine system information processing has pointed to the need to study AA of the advanced stages of information processing in complex systems, including decision-making and response execution. Crocoll and Coury (1990) evaluated the human performance consequences of automation reliability when applied to information acquisition and analysis as part of human-machine system performance. This work is relevant to the present research, as AA may be considered a form of unreliable automation. That is, depending upon the state of a system and its task, the automation may be turned "on" or "off". This may or may not occur with operator notification. In the latter case, the operator may in fact perceive AA as unreliable automation. Crocoll and Coury's (1990) work attempted to define the conditions under which automation reliability does or does not affect human performance. They compared information acquisition/analysis automation with decision automation. Subjects that were provided information acquisition/analysis automation performed better than subjects that received decision automation or both forms of automation when the automation was unreliable. This research has shown that people can adapt to automation unreliability when computer control is applied to low-level information processing functions. It has also been suggested that negative effects of automation unreliability may be more pronounced for decision automation than for information analysis automation (Parasuraman et al., 2000). Parasuraman et al. (2000), the only study to look at this issue, pointed to the need to further examine whether automation unreliability has greater negative effects on the later stages of human-machine system information processing than on monitoring and information analysis.

Toward this end, Parasuraman et al. (2000) formulated a model-based approach to automation of complex systems (e.g., Air Traffic Control systems) based on existing theories of human information processing. Four stages of human-machine system information processing are considered in their model, including Information Acquisition, Information Analysis, Decision-Making and Action Implementation. In addition, the level of automation of each stage is used to describe the overall degree of automation for the operation of a complex system. These stages correspond to aspects of human information processing included in historical pipeline models (e.g., Broadbent, 1958), such as perception, planning, decision-making, and action. The Parasuraman et al. (2000) model can be used to characterize various types of human-machine systems in terms of the aspects of information processing required for effective performance. They may also serve to categorize the functions of human-machine systems in terms of operator information requirements and stages of information processing. Therefore, the approach could be used to identify functions requiring higher-order cognition and facilitate examination of the application of AA to such functions and evaluation of the effect on human performance. In general, this method of automation design and evaluation needs to be evaluated through AA research.

Objectives

This research compared performance of a complex human-machine system under AA as applied to each of the four stages of human-machine system information processing presented in the Parasuraman et al. (2000) model. The objective of this work was to establish the impact of AA on cognitive task/function performance and to determine whether humans more easily adapt to dynamic allocations of psychomotor control functions than, for example, decision making.

The project extended previous work that indirectly assessed the implications of AA on cognitive function performance. Kaber (1997) investigated the application of AA to a dynamic control task involving functions that represented general stages of information processing, including formulating task processing plans and selecting among processing plan options. These functions required higher-order cognition of operators, including situation awareness (SA) and decision-making, for effective

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performance. The functions were adaptively allocated between a human operator and computer based on predetermined allocation schedules (times when automation was turned "on" and "off"). Kaber (1997) found that low to intermediate degrees of system automation improved operator SA and performance in comparison to manual control and full automation of all system functions. The adaptive allocation schedule appeared to significantly affect workload with longer periods of automation reducing subjective ratings of mental load. Unfortunately, the effects of AA for the planning and decision making functions of the dynamic control task were confounded by simultaneous AA of other functions, including system state monitoring and control action implementation. Therefore, the specific performance effect of AA of the decision-making component of the task could not be established. By studying AA of a complex system function representing a single stage of human information processing, while holding automation of all other functions fixed, the present research established the specific effect of AA on low-level sensory and psychomotor functions, as well as cognitive functions.

It was hypothesized that humans would not be able to adapt to AA of decision making and information analysis functions of complex systems as well as they are able to use AA of information acquisition and psychomotor functions, including action implementation. It was further posited that application of AA to the decision making aspect of dynamic control task performance would not be as effective as AA applied to the monitoring or information acquisition aspects of the task for managing operator workload.

Method

Participants

Forty-seven North Carolina State University students were recruited for this experiment. Participants consisted of both graduates and undergraduates who ranged in age from 18 to 28, including both men and women. All participants possessed 20/20 or normal corrected vision and were naïve to the task and its conditions. They were also required to have some degree of personal computer (PC) and video game experience. On a five-point scale ranging from one ("none") to five ("frequently"), the mean for PC experience was 4.8, and the mean for video game experience was 3.5. Seven of the participants were used in a pilot study to establish criterion levels for various dependent measures recorded during the actual experiment.

Tasks and Equipment

Two computer-based tasks, a dynamic control task (Multitask) and a secondary gauge-monitoring task, were used in this experiment. Both of these tasks were modified versions of the tasks employed by Kaber and Endsley (1997) and Kaber and Riley (1999) in studies of the performance and workload effects of AA in dynamic control tasks and the effectiveness of a psychophysiological-based approach to AA under different forms of DFA authority for managing operator workload. In the current experiment, the secondary task provided an index of primary task workload that was used to mandate automated control allocations. When operator performance in the secondary task fell below a predetermined level, the computer would mandate automated control of the primary task. Once performance in the secondary task returned to a level indicating an acceptable level of primary task workload, the Multitask simulation would return to manual control. There was no advance warning of the DFAs provided to operators. They were instructed to distribute their attention equally across both the secondary and the primary task.

Both tasks were presented through high-resolution computer monitors at 1024×768 pixels. The gauge task was presented on a 17-inch monitor using an 850Mhz Pentium® III workstation and controlled by participants with a standard keyboard. Multitask was presented on a 21-inch color monitor using an 800 MHz Pentium© laptop and controlled by participants with a 17-key numeric keypad and a mouse (see Figure 1).
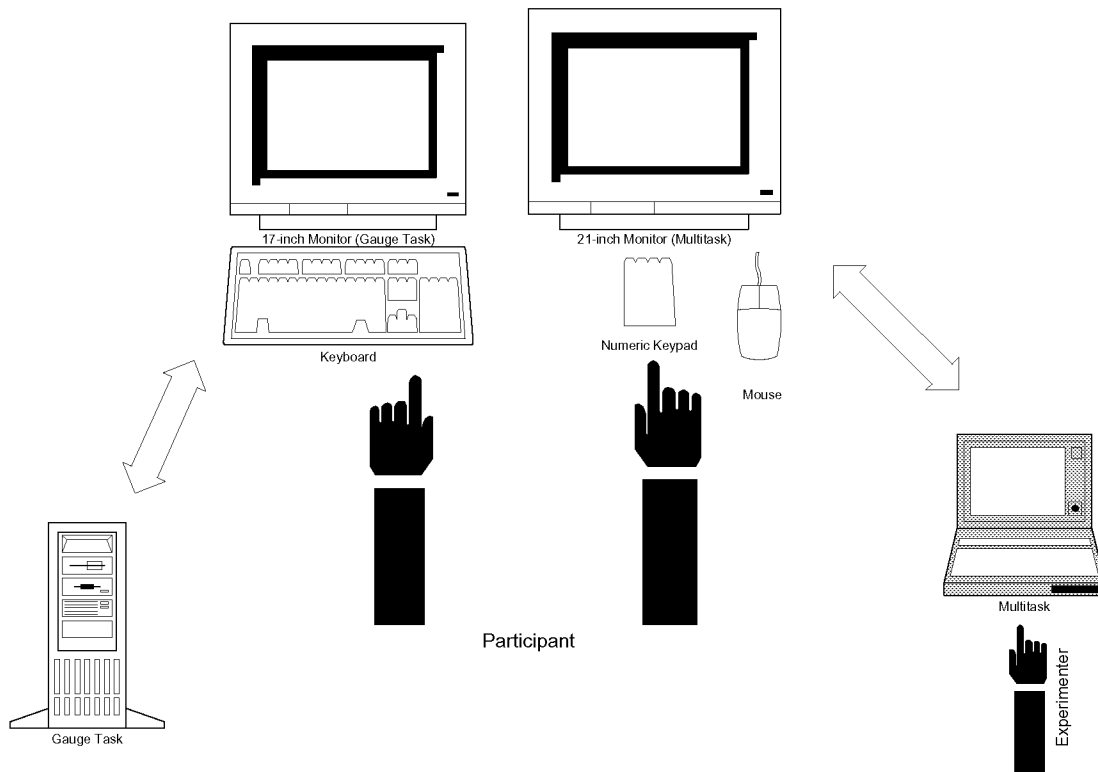
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Figure 1. Equipment layout.

Secondary Task. The gauge-monitoring task presented a fixed-scale display with a moving pointer (see Figure 2). Subjects were required to monitor vertical pointer movements to detect when a deviation occurred from a central "acceptable" range on the scale (colored in "green") into an "unacceptable" region (colored in "red"). The participants were required to correct for pointer deviations by pressing keys on the keyboard facilitating upward or downward pointer movements. Performance was recorded as a ratio of the number of off-nominal pointer deviations (i.e., the signal-to-noise ratio) missed/ number of total pointer deviations.
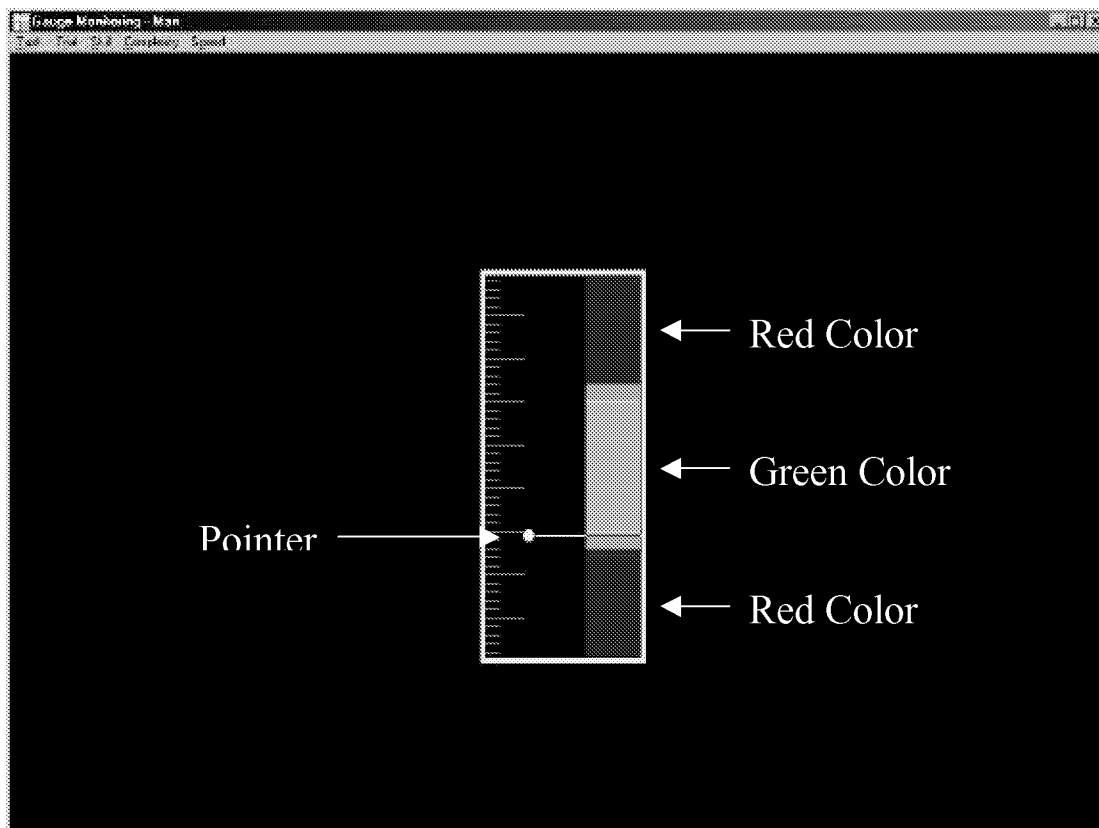
Figure 2. Secondary gauge-monitoring task display.

Primary control task. The Multitask simulation presented subjects with a radar scope display and revealed the position of different types of aircraft in a simulated airspace through the scope (see Figure 3). The aircraft were graphically represented by three types of icons (military, commercial, and private), which moved at different speeds toward an airport, or home base, at the center of the display (see Figure 4). The speed of each aircraft was dependent on its type. Military vehicles had the highest maximum speed, followed by commercial, and then private aircraft. All aircraft required between 60 and 120 seconds to reach the center of the display after their initial appearance on the radar scope.

The participant's task was to locate and "clear" the aircraft for landing before they reached the center of the display or collided with another aircraft. Clearing an aircraft required two steps, including establishing a communication link and issuing a clearance. To establish a communication link, participants had to move a cursor to the location of an aircraft using the mouse, and then press the left mouse button. The aircraft icon then flashed for several seconds, signifying a processing stage. After the icon stopped flashing, the subject had to click on the aircraft again, but with the right mouse button in order to issue a clearance. The aircraft icon flashed again, but this time for a significantly longer period. Once the icon stopped flashing on the second occasion, the clearance had been issued and the aircraft could safely fly to the home base. Clearing each aircraft required at least 30 seconds (approximately 7 seconds to establish a communications link and 23 seconds to process a clearance) and participants could clear multiple aircraft in parallel.
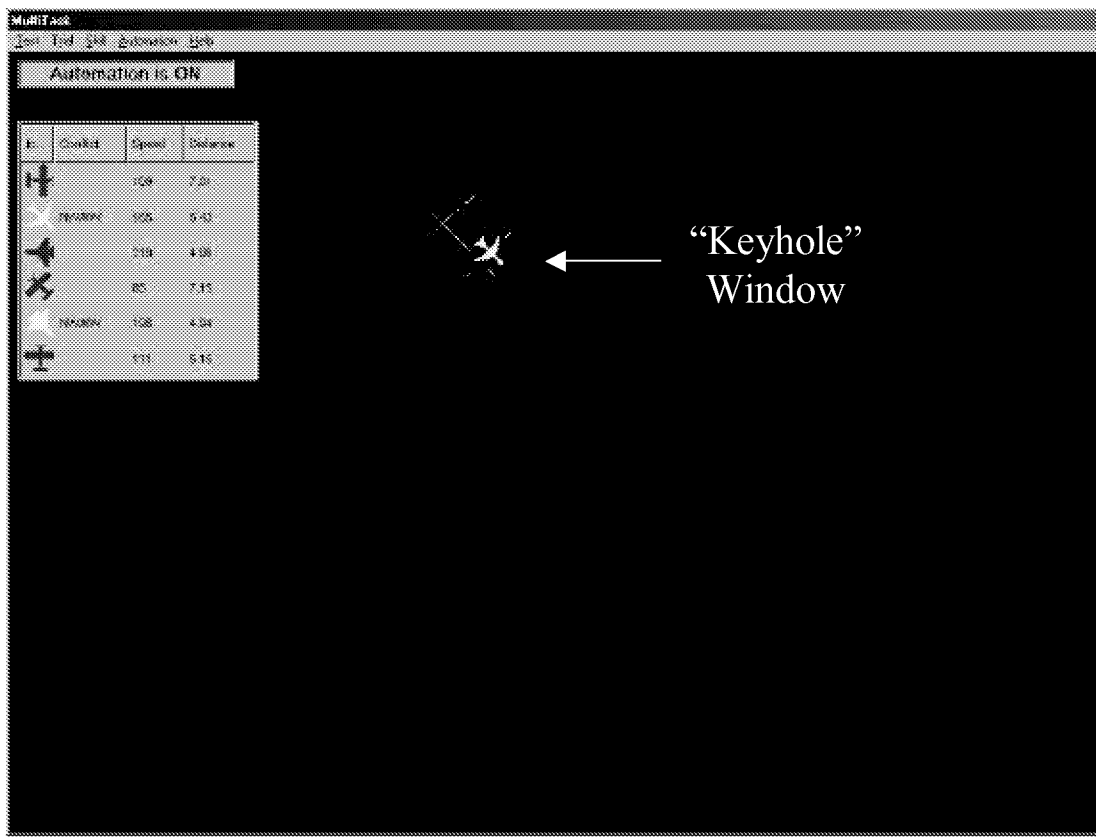
Figure 3. Primary control task display.

Private   Military   Commercial

Figure 4. Various aircraft types.

During all training and experiment trials, the majority of the radar display was not visible to the participants. A small portion of the display was made visible through a portal, or "keyhole" (see Figure 3), that could be moved by the participant in horizontal, vertical, and diagonal directions using the numeric keypad. Under certain Multitask simulation conditions, in order for subjects to clear aircraft from the radar scope, they had to first find them using the portal. The number and speed of the aircraft was set so it was nearly impossible to clear all vehicles appearing during each trial. In general, the simulation was designed to ensure that between five and six aircraft appeared on the radar scope at any given point in time.

The version of Multitask used in this experiment provided one of five different modes of automated assistance to each participant. Each mode was designed to assist with a particular stage of task information processing as described below:

Information Processing Modes

A *Manual* condition offered no assistance whatsoever.

An automated *Information Acquisition* mode was designed to provide computer control of the movement of the portal, which followed an inward spiral toward the center of the display. By pressing a key on the numeric keypad, participants could optionally have the portal "lock-on" to aircraft as they were revealed through the automated movement of the keyhole. With this feature enabled, the portal would move in its regular pattern around the display until it revealed any part of an aircraft. Once an aircraft was located, the portal would center itself on the vehicle and continue to follow the aircraft's path until the participant clicked with the right mouse button (to begin issuing a clearance) or released the portal from the aircraft by pressing another key on the keypad. This form of automation was considered an abstraction of implementing radar tracking systems into commercial ATC operations; that is, providing ATC with radar that actually tracks an aircraft versus using conventional scanning radar (Parasuraman et al., 2000).

An automated *Information Analysis* mode presented a decision aid as part of the Multitask radar display, which showed a table of all aircraft currently on the radar scope along with their properties. These included the type of aircraft, its direction of travel, speed, distance from the center of the display (home base), stage of processing (communication link, clearance), and information on whether or not the aircraft might be involved in a collision. Information on each aircraft was presented in a random order. This type of automation was considered to be similar to futuristic forms of ATC automation, including Electronic Data Displays (EDD), Trajectory Projection Aids (TPA), and Conflict Detection Aids (CDA) (c.f., Laois & Giannacourou, 1995).

A *Decision Making* condition was designed to present a decision aid similar to that used in the information analysis mode, but without the speed, collision, and distance information. Instead, the decision-making decision aid sorted aircraft for subjects according to priority for processing, from the top to bottom of the table. Highest priority was given to aircraft on collision courses with other vehicles, then to those aircraft closest to the center of the scope. This form of automation was considered to resemble a Clearance Advisory Aid (CAA) in real ATC (c.f., Laois & Giannacourou, 1995), except subjects in this research were required to effect the instructions of the Multitask automation when they are provided.

In the final mode, automated *Action Implementation*, a feedback display was integrated with the Multitask radar scope and presented the number of aircraft and their stage of processing. In this mode, participants only had to click on aircraft once in order to issue a clearance. The time to process aircraft was the same as in the other conditions, but the clearance was issued automatically after the communication link was established. Action implementation presented only five aircraft.

With respect to measurement of subject performance in the Multitask simulation, the number of aircraft cleared by an operator was recorded and divided by the number of aircraft presented (during each minute of the simulation). This yielded a percentage of the total number of aircraft processed. During experiment trials, the various modes of automated assistance could be switched "on" or "off" by the experimenter seamlessly through commands entered on a laptop, which presented an additional view of the primary task interface. Participants were unaware of the "Wizard of Oz" method, termed used here for the way DFA was implemented, taking place.

Adaptive Automation of Primary Task Functions

In general, this experiment was to study how the abstract manifestations of information acquisition and analysis, decision making and action automation impact human operator ability to function in complex system control. It was also conducted to establish whether dynamic control allocations of the various information processing functions between a human and computer could serve as an effective tool for managing human workload. The approach is akin to previous research (Laois & Giannacourou, 1995) that has attempted to identify forms of automated subsystems of ATC (e.g., EDD, TPA, CDA, CAA) that provide the greatest potential to aid human operators in their daily task completion. However, the present project focused on the adaptive delivery of automation and the potential implications of its use on cognitive task performance.

There are a number of strategies to AA, or methods for triggering DFAs, which have been defined in the literature (see Scerbo (1996) for a thorough review) including:

(A) Critical events – DFAs triggered by occurrence of events critically impacting system goals (e.g., malfunction) (Hilburn, Molloy, Wong & Parasuraman, 1993);

(B) Performance measurement – DFAs triggered by degradations in human monitoring performance below a criterion measure (Parasuraman, 1993);

(C) Psychophysical assessment – real-time assessment of operator workload (using for example physiological measures – electro-encephalogram (EEG) signals or heart-rate variability) as basis for decision to automate (Prinzel, Freeman, Scerbo, Mikulka, & Pope, 2000; Pope, Comstock, Bartolome, Bogart, & Burdette, 1994; Byrne & Parasuraman, 1996); and

(D) Behavior modeling – DFAs occur to human and computer to achieve predetermined pattern of overall system functioning (Rouse, Geddes & Curry, 1986).

(E) Similar to the psychophysical assessment strategy, Hancock and Chignell (1988) also proposed a strategy to AA involving comparison of current and future states of operator workload as well as system performance as a basis for DFAs.

For this experiment, a workload-based approach was taken to adaptive allocation of the information processing functions as part of the Multitask simulation. Subject performance on the gauge-monitoring task (secondary task workload) determined dynamic allocations of Multitask information processing functions to the human operator (manual control) or to the computer (automated control). Since the perceptual and cognitive demands of Multitask functions overlap those of the gauge-monitoring task, previous research (Kaber & Riley, 1999) has found the gauge-monitoring task to be a sensitive indicator of workload changes in the Multitask simulation, as effected by AA.

During the training sessions as part of the experiment, the average gauge-monitoring performance level and the standard deviation (SD) for the hit-to-signal ratio on pointer deviations was recorded. During the experiment trials, when performance of the gauge-monitoring task dropped below 1 SD of average task performance recorded during training for a particular user, the user was shifted to automated control in the Multitask simulation. While under automated control, when performance of the gauge-monitoring task reached 1 SD above average, users were returned to manual control of the Multitask simulation. These criteria were defined based on pilot data suggesting subject overload and underload at ±1 SD about mean performance, and Kaber and Riley's (1999) use of the coefficient of variation for secondary task workload, as a basis for DFAs in a similar task scenario.

Experiment Design and Independent Variable

A between-subjects design was used with modes, or levels, of automation as the independent variable in order to minimize the potential for Multitask training carry-over effects from one experimental trial to another. Four groups of subjects experienced AA as applied to one of the four stages of task information processing (information acquisition, information analysis, decision-making, action implementation).

For comparison purposes, two control conditions were also studied as part of the experiment. A completely manual control group performed the Multitask simulation with no automated assistance. These subjects also performed the secondary task in order to ensure a fair comparison of overall human-machine system performance across the AA and completely manual control conditions. The second control condition involved full automation of all functions as part of Multitask operation. In this condition, the computer processed all aircraft automatically as they entered the simulated airspace (appeared on the radar display). As in all other conditions, each aircraft required 30 seconds for complete processing (7 seconds to establish a communication link and 23 seconds to issue a clearance); however, the search time required for human operators to locate an aircraft in the airspace was virtually eliminated. (The computer system generated aircraft for processing and, therefore, stored their locations during the simulation.) This condition was investigated to establish the maximum performance capability of the automation. No subjects were used in evaluation of this condition, as no human control was required. With respect to the four AA conditions and the completely manual control condition, each test subject performed two trials at his or her assigned level of automation (LOA).

Response Measures

As previously mentioned, performance in the Multitask simulation was primarily measured in terms of the number of aircraft cleared, divided by the number of vehicles presented. An additional performance measure was calculated based on the number of potential aircraft collisions divided by the number resolved by an operator. (A near-collision was recorded when the buffer zones surrounding two aircraft intersected.) It is important to note that the Multitask simulation was preset to simultaneously present five aircraft at any point in time under the information acquisition and action implementation modes of operation, and six aircraft under those AA conditions involving information analysis and decision making aiding. These settings were selected based on pilot tests revealing that subjects could acquire and clear all aircraft under the information analysis and decision making modes for lower numbers of aircraft and to ensure that the level of workload across all AA conditions was approximately comparable. In an attempt to balance workload across conditions, four pilot subjects subjectively rated mental workload in the dual-task scenario under various AA conditions using the Modified Cooper-Harper scale. Results revealed a general correspondence among ratings for the simulation settings identified above.

As previously mentioned, performance in the gauge task was measured as the hit-to-signal ratio on pointer deviations (the number of unacceptable pointer deviations divided by the total number of deviations presented). For both tasks, the computer systems recorded performance observations on a per minute basis. The number of automation to manual control, or manual to automation mode, shifts that occurred during a trial was recorded along with the percentage of time spent in automated mode. Transitions between control modes only occurred at the end of a full minute during task performance. The measures on mode shifts and time under automation were intended to capture any effect of AA applied to the various aspects of human-machine system information processing on the rate of changes in operator workload or the frequency of dynamic control allocations. Subjective workload assessments were also captured using the NASA-Task Load Index (TLX) scale.

Procedure

The procedures for the experiment included: An introduction, completion of a background questionnaire and consent forms; 15 minutes of training in Multitask under the manual mode; 15 minutes of training in Multitask under the assigned LOA (subjects in the manual condition received a second 15 minute manual training period); 5 minutes of training in the gauge task; 20 minutes of training in the dual-task scenario under the assigned Multitask LOA with 2 minute cycles of manual and automated control; two 20-minute trials under AA at the assigned LOA (or completely manual control for the subjects included in the control group); and completion of NASA-TLX demand component ratings after each test trial.

A short break was provided to subjects after they completed the training trials and there was an extended (10 min.) break between the two test trials. During the first break between the final dual-task training session and the experimental trials, an experimenter calculated the average and SD of the hit-to-signal ratio for the gauge task performance. The first four minutes of the trial were excluded from this analysis, as this was the first time the subjects attempted the dual-task scenario and some time was allowed for them to become acquainted with the scenario. The mean and SD for each subject's dual-task practice were then input into the gauge-monitoring application for the experimental trials as criteria for control mode shifts.

During the experimental trials, an experimenter was notified when the performance criterion for a shift in control mode occurred. The notification also included a discreet beep from the computer presenting the gauge task. During all test trials, experimenters wore an earpiece in order to hear the sound from the gauge task without the subject being alerted as well. When a shift notification was given, an experimenter would press the space bar on the laptop computer that would change the mode of Multitask operation from manual control to automated control or vice-versa. This action was also done discreetly so that participants would not be aware that the experimenter was controlling the control mode shifts.

Data Analysis

All dependent measures were subjected to a two-way Analysis of Variance (ANOVA) with Level of Automation (LOA) as a between-subjects variable and trial as a within-subjects variable. The experimental design was replicated in order to produce an error term for evaluating the impact of the various LOAs on human-machine system performance and operator workload, as well as the role of individual differences in the results. In an attempt to assess the effectiveness of the experimental training protocol and to determine whether trial carry-over effects may have occurred, the trial number was included in all initial statistical models. If the trial term did not prove to be significant in these initial analyses, it was removed from the statistical model and the ANOVA was re-run on a reduced model in LOA. Accordingly, if the trial term was significant, it was retained in the full model. A LOA × trial interaction effect was also initially studied, but did not prove to be significant in the majority of the response models and was therefore dropped from those analyses.

Duncan's Multiple Range (MR) test was used to further investigate any significant effects revealed by the ANOVAs. An alpha-level of 0.05 was used to establish statistical significance of any effects and as a basis for identifying significantly different factor settings (except where noted otherwise). Residual and normal probability plots were generated in order to assess conformance of the experimental data with the assumptions of the ANOVA, including normality and constant variance. In addition, all data sets were subjected to Shapiro-Wilks test for normality. In the event that the Shapiro-Wilks test statistic was significant ($p<0.05$), appropriate transforms on the response measures and predictors were considered. If outliers were identified based on graphical analysis using the residual plots, a regression analysis was conducted on the data set using SAS and Cook's D values, as well as the SAS DFFIT's statistic, were determined in order to more objectively identify outlying observations. Based on the plots and the indicators of the strength of specific observation effects on the statistical model, outliers were identified. If both the Cook's D value and the SAS DFFIT's statistic indicated that a specific observation was an outlier, or if either one of the measures indicated that a specific observation was an extreme outlier, the observation was removed from the data set.

Performance Measures

For the statistical analyses of the performance measures, observations were separated into two sets of data, one that included performance while in manual mode and a second that included performance while in automated mode. For each subject, Multitask and gauge monitoring performance was averaged across the automated minutes of a trial to obtain a single score for each trial. Similarly, performance observations under manual minutes were averaged to obtain a single score for each trial. Thus, for each subject, there were four performance measures, including: (1) Multitask performance while under manual control; (2) Multitask performance while under automated control; (3) gauge-monitoring performance while manually controlling the Multitask simulation; and (4) gauge-monitoring performance while Multitask was automated.

With respect to performance under automation, only the four levels of the independent variable representing automation of the four stages of information processing were considered. Therefore, each data set included 64 observations (4 LOAs × 8 subjects × 2 trials). However, one subject logged 0 minutes under automated control in both of the test trials. Beyond this, using the method described above for identifying outliers, 5 observations on Multitask performance under automated mode were removed from the data set. Thus, 57 observations remained for analysis. With respect to gauge-monitoring performance under automated control, 2 outliers were removed the data set, resulting in a total of 60 observations for analysis.

In regard to the Multitask and gauge-monitoring performance measures under manual control, five levels of the LOA variable, including the completely manual control condition, were considered in the analysis. Consequently, each data set included 80 observations (5 LOAs × 8 subjects × 2 trials). With

respect to the data on Multitask performance under manual control, 3 outliers were removed, resulting in a total of 77 observations. Finally, two outliers were removed from the data on gauge-monitoring performance under manual control, resulting in a total of 78 observations.

Automation Shifts

The total number of minutes under automated versus manual control was summed for each trial. This number was divided by 20 minutes (the test trial duration) to obtain the percent time under automated control for each trial. In addition, the number of shifts in the mode of control was counted for each trial. Both of these measures applied only to the four AA conditions; thus, the data sets included 64 observations each (4 LOAs × 8 subjects × 2 trials). With respect to the number of minutes under automated control, 3 outliers were removed from the data set, resulting in a total of 61 observations. Only one outlier was removed from the data on the number of automation shifts during trials, resulting in a total of 63 observations for analysis purposes

Workload Measures

Following each trial, subjects rated task workload using the NASA-TLX. The individual demand component ratings were combined with the component rankings collected at the onset of the experiment in order to calculate an overall/weighted workload score. This overall score and highly ranked demand components, including temporal load, were subjected to the two-way ANOVA described above. These analyses were completed both with and without observations on subjects included in the manual control condition. That is, the full data set of 80 observations was analyzed as well as the subset of 64 observations that represented only the AA conditions. With respect to the overall workload scores, 2 outliers were removed from the data; therefore, data sets including 78 and 62 observations were analyzed. In regard to the temporal load ratings, 4 outliers were removed the data. Consequently, data sets of 72 and 60 observations were analyzed.

Results

Performance Measures

Primary Task Performance. The analysis of Multitask performance under automation revealed a significant effect due to trial ($F(1,32)=9.26$, $p<0.01$) with performance in the second trial being significantly superior. There was a trend in the data indicating an effect due to LOA, which proved to be marginally significant ($F(3,27)=2.76$, $p<0.1$). A post-hoc analysis of this trend using Duncan's MR test with an alpha level of 0.10 revealed that performance under automation of action implementation may be substantially higher than performance under the three other automation conditions (information acquisition, information analysis, and decision making). Figure 5 presents the mean Multitask performance for each AA condition, fully automated processing, and the completely manual control mode. The data on the fully automated condition was not included in the statistical analysis and is presented for comparison purposes only. Note: All figures present the information processing stages and/or trial data in the sequence and gray-scale shading as presented in the figure legends.

The analysis of Multitask performance under manual minutes indicated no significant main effect due to LOA (also shown in Figure 5). However, there was a significant LOA by trial interaction ($F(4,32)=3.62$, $p<0.05$). According to post hoc analysis, performance in the manual mode of the primary task during the second trial for those subjects under the condition applying AA to the action implementation function was significantly better ($p<0.05$) than manual performance in all other LOAs and trials. In addition, the second trial of the manual control condition resulted in significantly poorer performance than all of the other LOA conditions and trials, with the exception of the first trial of the

manual control condition and the first trial of the condition applying AA to the decision making aspect of the Multitask simulation (see Figure 6). Note: All graphs are presented in grayscale format and the shading of the graph bars correspond to legend index shading. Additionally, the legend index corresponds to the sequential graph bar presentation (e.g., first bar corresponds to "information acquisition"; second bar to "information analysis").
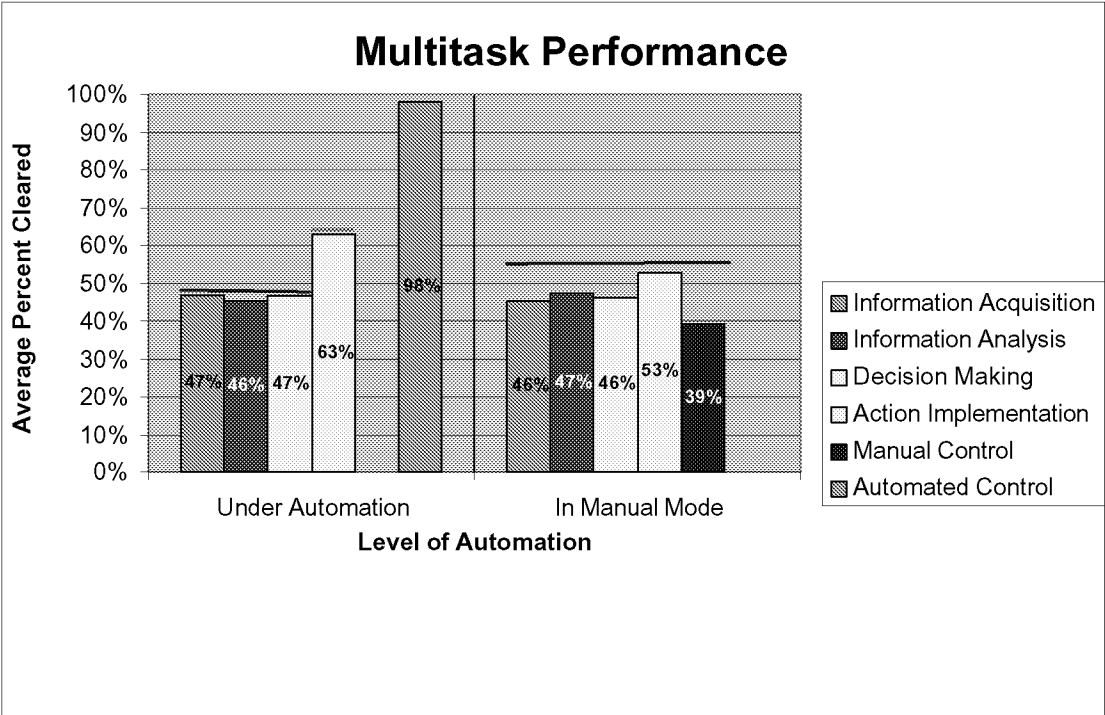

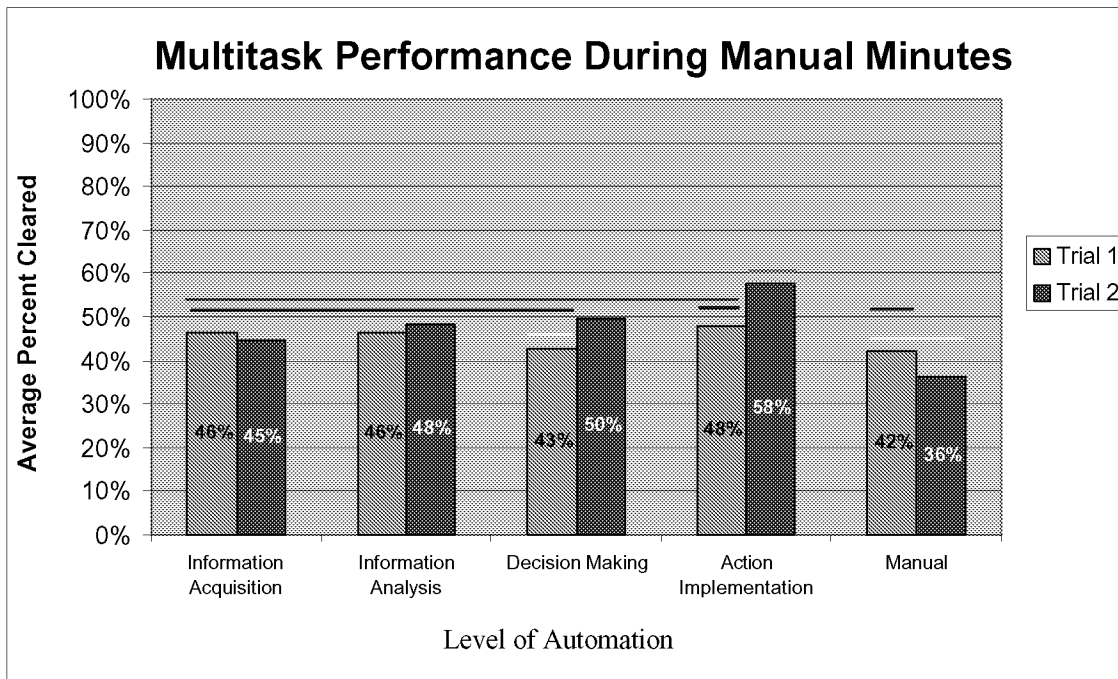Figure 5. Primary task performance under automated and manual control.

Figure 6. Primary task performance during manual minutes by LOA and trial.

Since the LOA by trial interaction generally indicated that there were greater differences due to LOA in the second trial than in the first, the data from the second trial was analyzed separately in order to determine whether there was a main effect due to LOA during the second trial. The analysis revealed a significant effect due to LOA ($F(4,34)=2.98$, $p<0.05$). Duncan's MR test revealed that performance in the primary task under manual control as part of the condition applying AA to the action implementation function was significantly better than performance under manual control in the completely manual control condition (see Figure 7).

It may have been possible that the second test trial was more sensitive for revealing performance differences due to the LOA as operators had the experience of the first test trial to refine their strategies to exploit the features of the AA as applied to the various information processing functions. It appeared that AA of action implementation positively influenced operator manual control of the simulation as part of this condition in comparison to strictly manual performance. In general, Figure 7 suggests that there was a trend for better manual control performance as part of the AA conditions, as compared to the completely manual control condition.

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Multitask Performance, Manual Minutes, Trial 2

(Bar chart showing Average Percent Cleared vs Level of Automation)
- Information Acquisition: 45%
- Information Analysis: 46%
- Decision Making: 50%
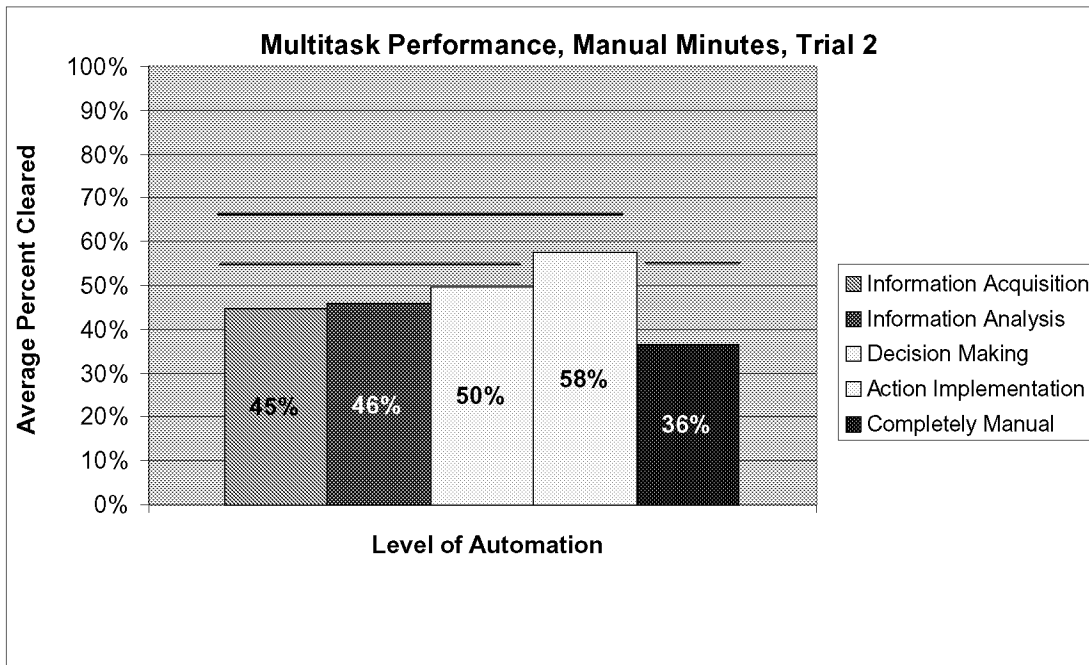- Action Implementation: 58%
- Completely Manual: 36%

Figure 7. Primary task performance while under manual control in the second trial.

Secondary Task Performance. The analysis of performance on the gauge-monitoring task during automation of the Multitask simulation indicated a significant effect due to LOA ($F(3,27) = 3.41$, $p<0.05$). Post hoc analysis revealed that the hit-to-signal ratio in the secondary task was significantly higher (indicating lower workload) when AA was applied to the information acquisition and action implementation functions of the primary task, as compared to when it was applied to information analysis (see Figure 8). The decision aids provided as part of the information analysis and decision-making conditions included additional visual displays (compared to automation of information acquisition and action implementation) that may have increased both visual attention and cognitive processing loads for operators leading to poorer gauge performance under automation of those conditions. During the manual minutes, there was no significant effect due to LOA (see Figure 8); however, there was a highly significant effect due to trial ($F(1,40)=12.81$, $p<0.005$). Post-hoc analysis revealed gauge-monitoring performance (workload) to be significantly worse during the second trial than the first (see Figure 9). Although not significant, a similar difference in performance scores for the first and second trials was observed for automated control.

It is possible that subjects may have been slightly more fatigued in the second trial, as compared to the first. Another possibility is that subjects shifted their attention away from the secondary task and to the primary task over time. This is supported by the increase in performance in the primary task during the second trial, as compared to the first; however, this observation was only statistically significant when automated control was used.
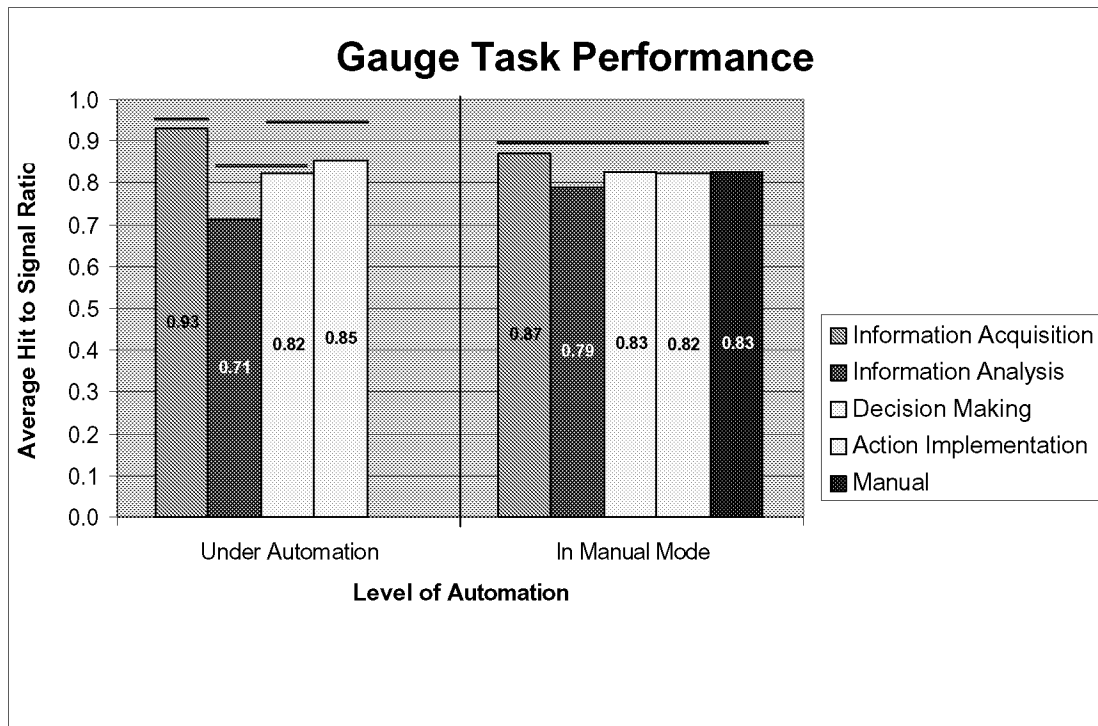
Figure 8. Gauge task performance by LOA under automated and manual control.
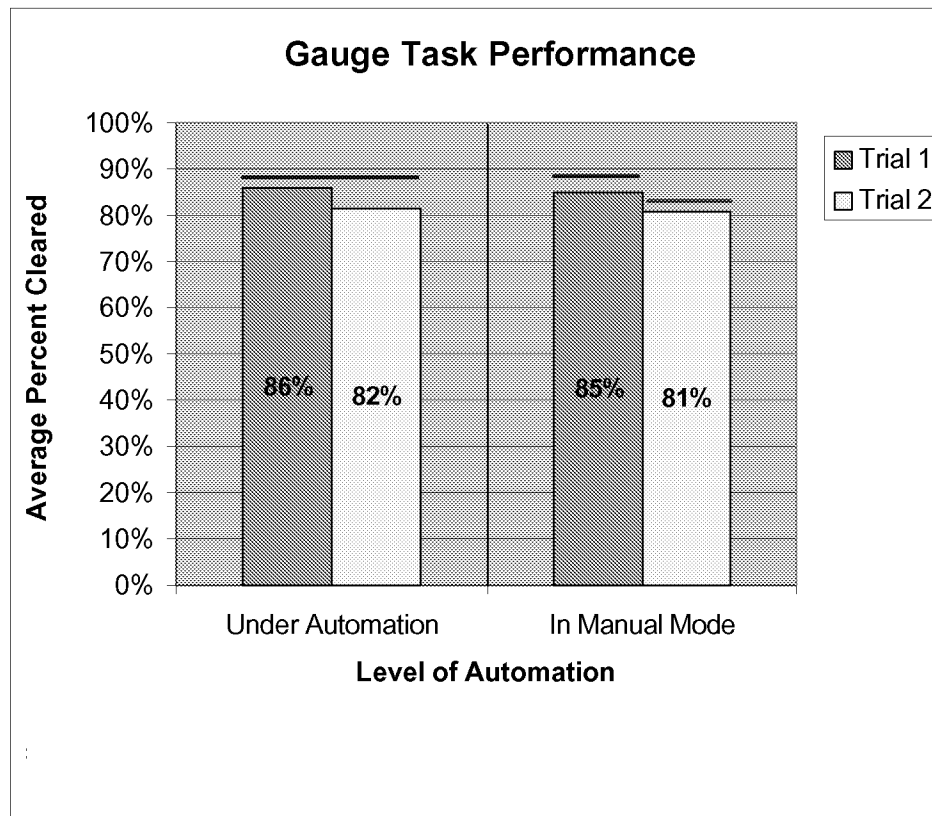
Figure 9. Gauge task performance by trial under automated and manual control.

Automation Shifts

The analysis of percent time under automation revealed no significant effect due to LOA, however, there was a significant main effect due to trial ($F(1,32)=9.44$, $p<0.005$) (see Figure 10). Duncan's MR test revealed that the time spent in under automated control was significantly greater in the second trial than in the first. This result is related to the significant trial effect seen for gauge-monitoring performance. Since the shifts from manual control to automation in the primary task occurred when gauge-monitoring performance was poor, and performance in the gauge-monitoring task was generally worse during the second trial than in the first, it is logical that automation was invoked for longer periods in the second trial.

Although there appeared to be a large difference in the percentage of time-on-task under action implementation automation (31%) versus information acquisition automation (18%), the difference was not statistically significant. Upon closer examination of the time data, it was observed that, on average, subject spent 26% of task time in an automated mode; however, the overall SD was 20%.
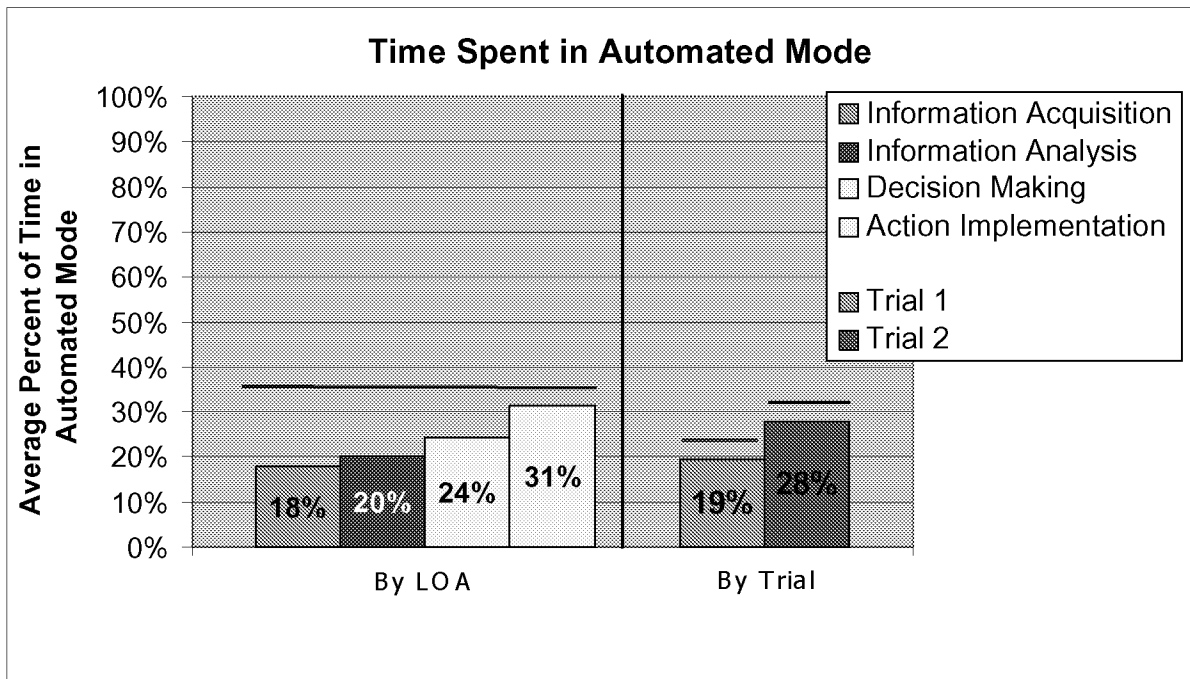
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Figure 10. Average percent time under automation by LOA and by Trial.

The analysis of frequency of shifts between control modes revealed a significant effect due to LOA ($F(3,28)$ = 3.37, $p<0.05$) (see Figure 11). Post hoc analysis revealed significantly fewer automation control shifts under AA as applied to information analysis compared to AA as applied to action implementation.

The low number of shifts under the information analysis condition can be explained by referring to performance in the gauge-monitoring task as part of this condition. Subjects performed worse under automation of the primary task than when using manual control (see Figure 8). However, the algorithm used to cause shifts in primary task control assumed performance would improve under automation. Subjects in the information analysis AA condition were less likely to shift to automated control since this required their manual control performance during the test trials to be worse than their average performance under both automated and manual control modes recorded during practice. If they did shift into the automated control mode, they were even less likely to return to manual control since this required that their performance under automated control be better than their average performance under both automated and manual control.
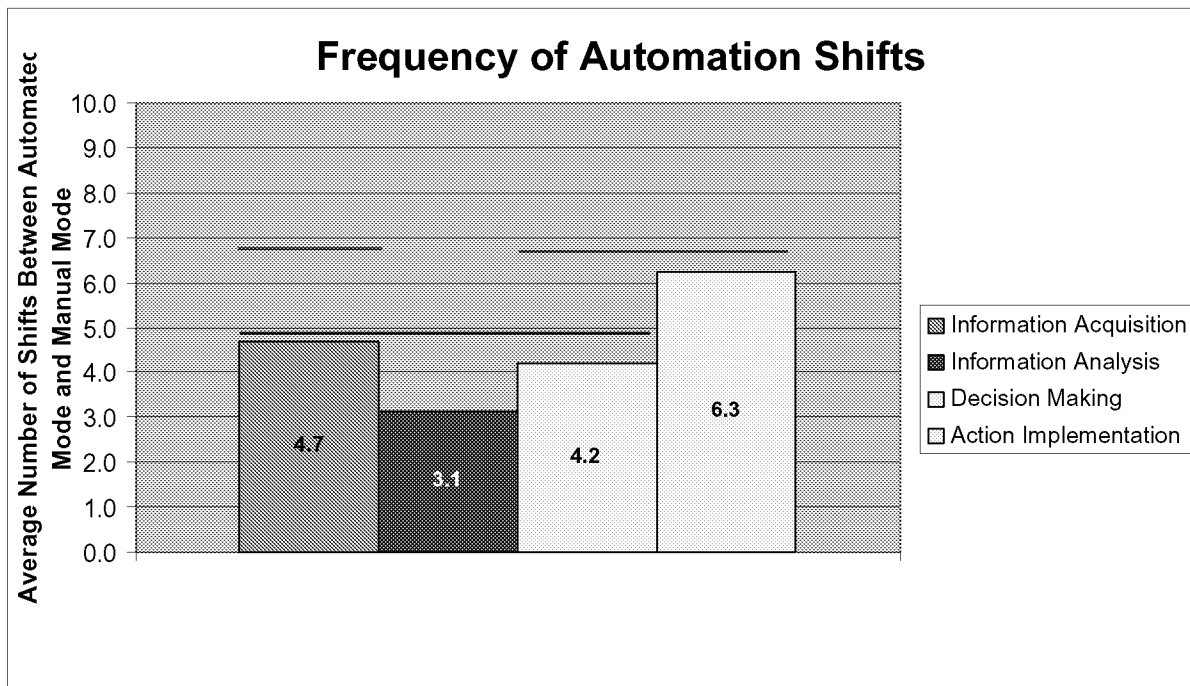
Figure 11. Average number of shifts between automated and manual control by LOA.

Workload Measures

The analysis of the overall workload scores revealed no significant differences between the AA conditions and the completely manual control condition. The analysis of temporal load ratings revealed a trend due to LOA ($F(4,34)=2.4$, $p<0.1$).When the observations on the manual control condition were excluded from the analysis and only the AA conditions were compared, a significant effect due to LOA was revealed ($F(3,27)=3.03$, $p<0.05$). Post hoc analysis revealed that subjects assigned to the conditions applying AA to information analysis and action implementation functions rated their temporal load higher than subjects experiencing AA applied to information acquisition (see Figure 12). When AA was applied to the information acquisition function, the search for aircraft on the radar scope was automated (the computer moved the portal) and the task, in general, became machine-paced instead of operator-paced. This may have caused subjects to perceive less time pressure in the completion of the task.
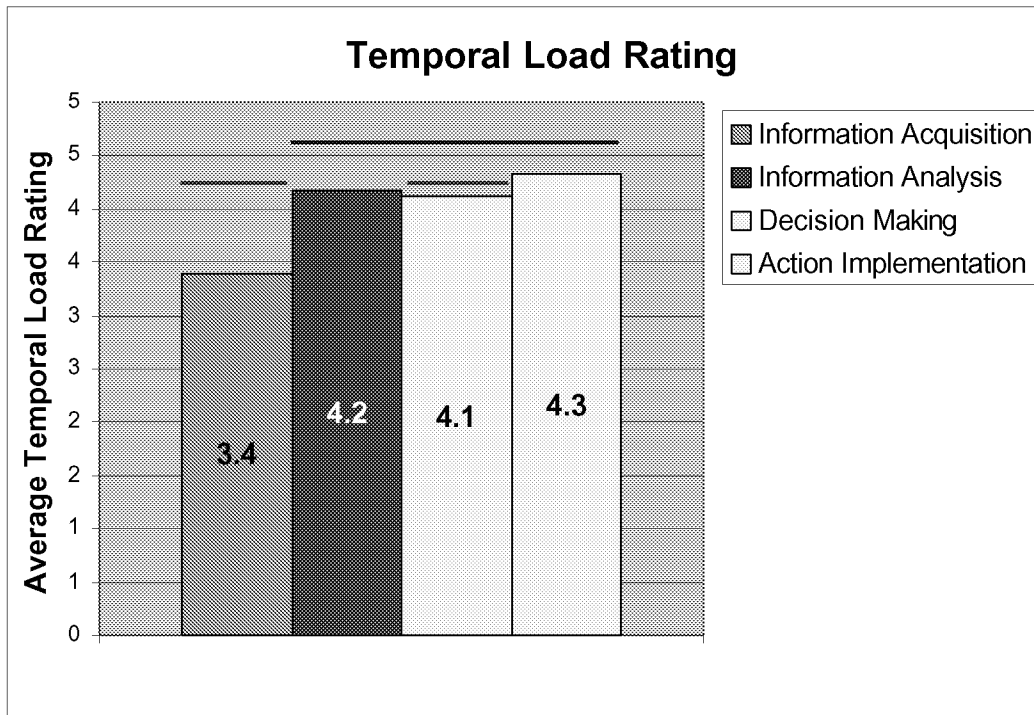
Figure 12. Average rating of temporal load across AA conditions.

Discussion

These results provide evidence that the effectiveness of AA is dependent on the stage of task performance (human-machine system information processing) that is flexibly, or adaptively, automated. In general, the final stage of action implementation appears to be well suited to AA. Primary task performance was greatest when automation was applied to the implementation aspect of the task. More importantly, manual control performance as part of AA of action implementation was better than under the other AA conditions and the completely manual control condition. This suggests that automation of the action implementation stage of processing influenced performance during the manual mode of operation.

Considering the results on secondary task performance on the gauge task, or the workload measure, signal detection performance was greater for both automated and manual minutes when AA was applied to the information acquisition aspect of the task, particularly when compared to automated control as part of AA of the information analysis function. The automation under the information acquisition condition appeared to relieve some task time pressure for subjects, as the computer automatically controlled the motion of the portal in searching for aircraft and allowed subjects more time to attend to the secondary task. In contrast, automation of information analysis appeared to reduce the time available to attend to the secondary task. It is possible that the decision aid display as part of this condition held operator attention in their attempts to affect an optimal processing strategy. In general, the complexity of the automation and visual attention required of the displays may have caused an increase in primary task workload.

Contrary to expectation, the results on control mode shifts demonstrated that the AA strategy investigated here was ineffective for managing operator workload under the information analysis. This was primarily due to the characteristics of the automation. The decision aid as part of this condition appeared to induce more cognitive processing of Multitask information, specifically investigating potential collisions and prioritizing aircraft for clearances based on their characteristics. This may have lead to ineffective implementation of AA because the DFA trigger criterion used in the experiment assumed that automation would provide some workload relief to subjects. Beyond this, the AA strategy appeared to be highly sensitive to operator workload fluctuations when AA was applied to the psychomotor (action implementation) aspect of the task. It was initially hypothesized that the AA strategy would be less effective for the decision-making automation condition in comparison to the information acquisition automation condition; however, there were no significant differences among these settings of LOA in terms of percentage of time-on-task under automation or the number of control mode shifts.

All these results suggest that humans are better able to adapt to AA when applied to lower-level sensory and psychomotor functions, such as information acquisition and action implementation, as compared to AA applied to cognitive (analysis and decision making) tasks. Finally, the results also provide support for the use of AA, as compared to completely manual control. In comparing performance under the manual control condition with both automated and manual control periods as part of the various AA conditions, performance was always better under AA with the exception of the first trial applying AA to the decision making function. This finding suggests that, given the forms of AA investigated in this study, some AA, supporting early stage information processing, is better than none at all. However, significant research questions still remain to be addressed including the effects of cognitive overhead, "trust" in automation and integrity, cognitive costs associated with different levels of IP support through adaptive automation, and how adaptive automation impacts situation awareness at different stages of information processing. Research is currently underway to address these and other human factors issues identified with this new, but exciting approach, to human-centered automation design.

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13. ABSTRACT *(Maximum 200 words)*

Adaptive automation (AA) has been explored as a solution to the problems associated with human-automation interaction in supervisory control environments. However, research has focused on the performance effects of dynamic control allocations of early stage sensory and information acquisition functions. The present research compares the effects of AA to the entire range of information processing stages of human operators, such as air traffic controllers. The results provide evidence that the effectiveness of AA is dependent on the stage of task performance (human-machine system information processing) that is flexibly automated. The results suggest that humans are better able to adapt to AA when applied to lower-level sensory and psychomotor functions, such as information acquisition and action implementation, as compared to AA applied to cognitive (analysis and decision-making) tasks. The results also provide support for the use of AA, as compared to completely manual control. These results are discussed in terms of implications for AA design for aviation.

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