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ADAPTIVE AUTOMATION AND HUMAN PERFORMANCE: I. MULTI-TASK PERFORMANCE CHARACTERISTICS

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The present investigation had three major objectives: (1) Develop software that provides a robust and sensitive set of flight-relevant tasks. (2) Provide operator performance data for each flight task under normal (manual), single-task conditions (3) Evaluate the sensitivity of operator performance on each task to changes in task difficulty and in the number and type of concurrent tasks performed. The overall goal was to provide an empirical "baseline" from which the results of future adaptive-automation studies (in which task difficulty and operator workload would vary) could be successfully interpreted.
Overall, the three studies were successful in meeting the first major goal of the adaptive automation research program: to establish a baseline of empirical performance data in a multi-task flight-simulation environment. These results will help in the design and interpretation of results of future adaptive-automation studies that will be carried out as part of this research program.

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SUMMARY

This technical report is the first in a series that describes the results of empirical studies of the efficacy of adaptive automation (or adaptive functional allocation) on the performance of flight-relevant tasks. The studies support a program of research whose goal is to identify and develop human performance-based design principles for the application of adaptive automation technology. The investigations are also designed to evaluate and validate alternative adaptive automation concepts.

The present investigation had three major objectives: (1) Develop software that provides a robust and sensitive set of flight-relevant tasks. (2) Provide operator performance data for each flight task under normal (manual), single-task conditions. (3) Evaluate the sensitivity of operator performance on each task to changes in task difficulty and in the number and type of concurrent tasks performed. The overall goal was to provide an empirical "baseline" from which the results of future adaptive-automation studies (in which task difficulty and operator workload would vary) could be successfully interpreted.

Three tasks were carried out in support of these objectives.

First, extensive software changes were made to an existing multi-task flight-simulation package, the Multi-Attribute Task Battery (MAT), which includes tracking, monitoring, fuel management, and ATC communications tasks (Comstock & Arnegard, 1990). The revised MAT software enabled independent manipulation of parameters of each flight task under either manual or automated performance modes. Successive iterations of software development and informal user testing led to a version that is suitable for the needs of the experiments to be carried out in the next year of the project.

Second, a pilot study with 12 subjects was carried out to evaluate the sensitivity of the revised MAT tracking task to manipulations of task difficulty and practice, using either a joystick or a mouse as the control device. The results established an appropriate level of difficulty (driving function frequency) for the tracking task. The results also indicated that extensive practice was not

required to reach stable performance levels on this task. Satisfactory performance data were obtained with either control device, but the joystick was chosen for subsequent studies because of operator preference and its greater similarity to cockpit control devices.

Third, an experiment with 8 subjects was carried out to examine the effects of task combination (single-, dual-, and multi-task) on performance of the tracking, monitoring, and fuel management tasks. Performance on each task decreased systematically from single-task to dual-task and from dual-task to multi-task combinations. However, the tracking and monitoring tasks were the most sensitive to task combination; performance on the fuel-management task was less sensitive, probably due to high inter-subject variability. The performance profiles obtained were consistent with operator limitations in perceptual/cognitive processing resources or in structural (input/output) factors,. However, it was argued that resource scarcity was the major source of performance decrement. Taken together with the data from the pilot study, the results established the sensitivity of the tracking, monitoring, and fuel management tasks of the revised MAT battery to variations in task difficulty and task load.

Overall, the three studies were successful in meeting the first major goal of the adaptive-automation research program: to establish a baseline of empirical performance data in a multi-task flight-simulation environment. These results will help in the design and interpretation of results of future adaptive-automation studies that will be carried out as part of this research program.

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INTRODUCTION

Background: What is Adaptive Automation?

Recent technological advances have made viable the implementation of intelligent automation in advanced tactical aircraft. The use of this technology has given rise to a number of new human factors issues and concerns (NASA, 1989; Wiener,1988). Errors in highly automated aircraft have been linked to the adverse effects of automation on the pilot's system awareness, monitoring workload, and ability to revert to manual control (Chambers & Nagel, 1985; Hart & Sheridan, 1984; Parasuraman, 1987; Wiener, 1988). These problems have been attributed to *technology-centered* automation design, in which engineering advances largely determine whether and how automation is introduced into the cockpit, as opposed to *human-centered* design, which also takes into account pilot capabilities and limitations in using automation (NASA, 1989).

Partly in response to these concerns, *adaptive* automation[1] or automation that is implemented dynamically in response to changing task demands on the pilot, has been proposed (Rouse, 1988). Adaptive automation may be superior to nonadaptive or "traditional" automation because it is thought to improve pilot situational awareness, increase task involvement, regulate workload, enhance vigilance, and maintain manual skill levels (Hancock, Chignell, & Lowenthal, 1985; NASA, 1989; Noah & Halpin, 1986; Parasuraman, 1987; Parasuraman & Bowers, 1987; Rouse, 1976, 1988; Wickens & Kramer, 1985). At present, however, empirical evidence for the efficacy of adaptive automation is lacking. In a review of the literature on adaptive automation, Parasuraman, Bahri, Deaton, Morrison, & Barnes (1990) found few laboratory or field studies of the effects of adaptive automation on pilot performance. If adaptive automation is to be a viable cockpit design option, more needs to be learned about its effects on performance under different flight conditions.

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[1] Also referred to as "adaptive aiding" and "adaptive function allocation."

The report by Parasuraman et al. (1990) provides an extensive discussion of various aspects of the application of adaptive automation to flight operations. The reader may consult this report for details concerning such issues as the various types of adaptive automation, the logic used by the adaptive system to implement task changes, the question of pilot consent to suggested adaptive changes, and so on. For example, adaptive automation may include *allocation, transformation, or partitioning* of piloting tasks (Rouse, 1988). The adaptive logic may use a number of different procedures to initiate task changes, for example mission requirements, the designer's *model* of the pilot's behavior (including pilot intentions), or the actual *measurement* of pilot behavior (including physiology), whether off-line or on-line (Parasuraman et al., 1990). The task changes identified by the adaptive system may require the pilot's consent, as is conceived in Lockheed's Pilot's Associate project, or the adaptive system may initiate the changes autonomously after informing the pilot. For the purposes of the present series of studies we assume a relatively simple adaptive system in which the system allocates tasks to either the operator or the computer. No special form of adaptive logic is assumed and operator consent is not sought (although the adaptive task changes are not implemented without informing the operator). These limitations are necessary as a starting point because the studies we are conducting are the initial empirical studies investigating the effects of adaptive automation on operator performance. In subsequent studies we will examine more complex modes of adaptive automation (e.g., involving performance-based adaptation and operator consent).

Program of Research

The aim of the present program of research is to investigate issues related to the efficacy of adaptive automation in a series of experiments examining performance on several simulated flight-related tasks. Any adaptive automation scheme, irrespective of the adaptive logic used or the task changes implemented, involves *transitions* or changes from one level of automation of a task to another. Our overall goal is to understand the impact on performance of both the dynamics of such transitions as well as the static demands associated with each level of automation in isolation. For example, a particular flight function may be automated for long periods of time, then be carried out manually for a short period, and then revert for another long period to automated control. We refer to this as *long-cycle* adaptive automation. At the other extreme, in *short-cycle* adaptive automation, a given flight function may be cycled between manual and automated control quite frequently, particularly if the adaptive logic is very sensitive to small changes in task demands or pilot workload.

Our studies will examine the effects of both short-cycle and long-cycle adaptive automation on performance in a multi-task environment. We plan to use a cost-benefit approach to studying the efficacy of adaptive automation. Our experiments will be designed to obtain empirical evidence for the claimed beneficial effect of adaptive automation on performance as well as to document the existence of possible costs.

Present Studies

Our initial efforts are aimed at investigating the effects of both short-term and long-term shifts in adaptive automation (i.e., task allocation) on the performance of flight-relevant tasks that tap three broad information-processing domains: perceptual-cognitive (system monitoring), cognitive-strategic (fuel management), and perceptual-motor (tracking). As discussed in the Parasuraman et al. (1990) review, a few studies have examined the effects of automation on human performance, but these studies have mostly used static automation, i.e. where the set of tasks that are automated and manual remains fixed (Fuld, Liu, & Wickens, 1987; Idaszak & Hulin, 1989; Kibbe & Wilson, 1989; Wickens & Kessel, 1981). Studies have not been conducted in which operators are cycled through phases of manual and automated performance of a task, which is a key aspect of adaptive automation. In order to determine whether adaptive automation has positive effects on performance as claimed, automation effects need to be examined in conditions where operators are shifted between manual and automated conditions rather than always perform in a manual or an automated mode.

In the present report we describe the development of our multi-task capability and present an empirical evaluation of its performance characteristics. This will provide the basis for investigating effects of automation shifts on performance, which is described in the second report in this series. The main goals of the present study were:

- To develop a robust and sensitive set of flight-relevant tasks. Major sub-goals for this goal include: (1) the ability to sample performance data continuously; and (2) change task parameters flexibly (i.e. those required for a broad range of adaptive-automation studies) without having to make major software changes.

- Provide "baseline" performance data for each task in isolation that will be useful in interpreting performance changes in future adaptive-automation studies using the same tasks.

- Evaluate the sensitivity of task performance to changes in task difficulty and in the number and type of other concurrent tasks.

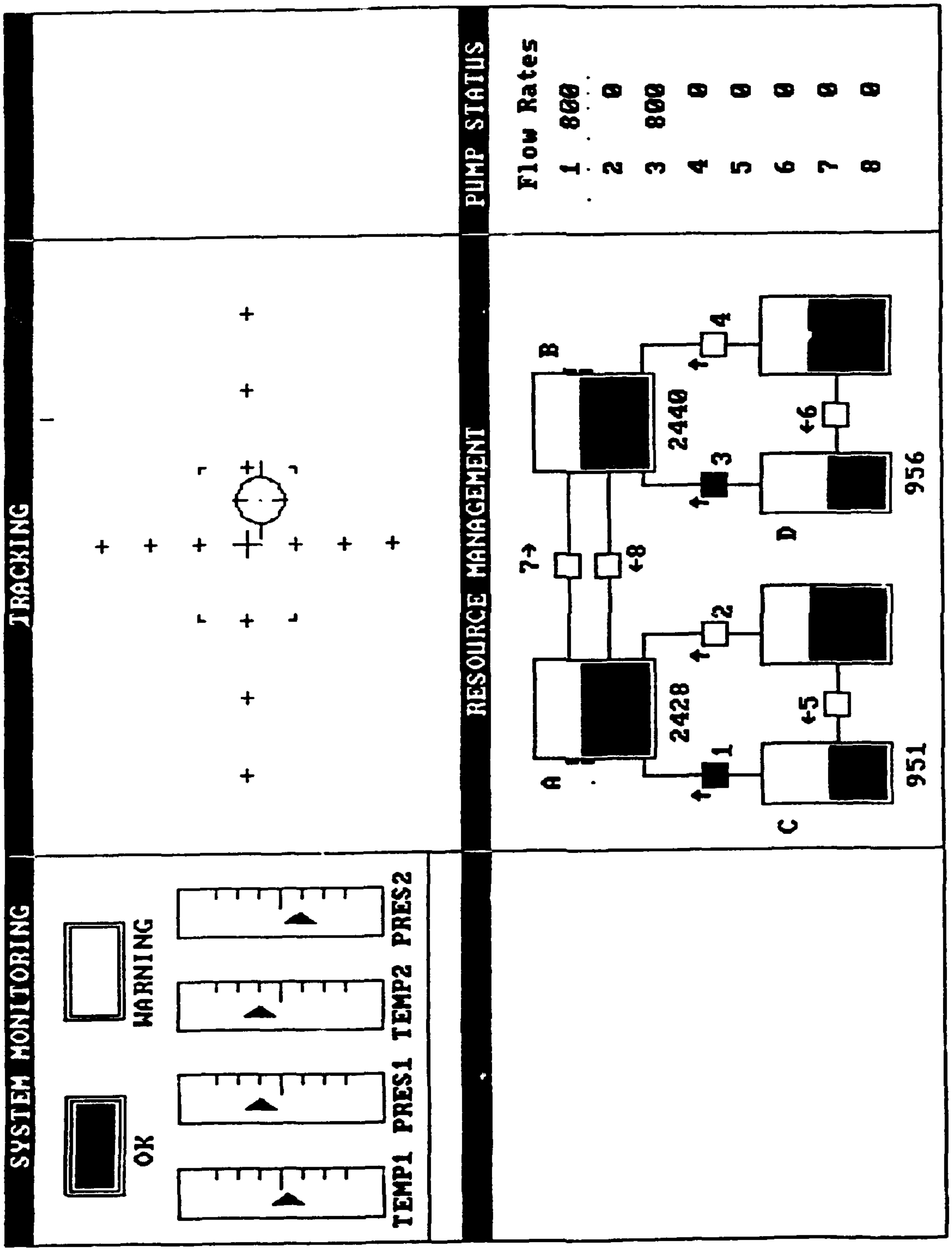
The present report provides a description of three main tasks that were carried out in the initial phase of our research program. First, an existing multi-task flight-simulation package, the Multi-Attribute Task Battery (MAT) (Comstock & Arnegard, 1990), was extensively revised. The MAT software, which includes tracking, monitoring, fuel management, and ATC communications tasks, was revised to support our empirical studies on adaptive automation. Next, the results of a pilot study are presented. The aim of the pilot study was to obtain measures of performance of one of the tasks of the revised MAT, tracking, under different levels of task difficulty and as a function of control input (joystick versus mouse) and practice. Finally, the results of an experiment investigating single- and multiple-task performance characteristics of the MAT battery are reported.

SOFTWARE DEVELOPMENT: EXTENSION OF THE MAT BATTERY

In order to begin our investigations of adaptive automation and human performance, we needed to develop a benchmark set of tasks to be used in simulations of flight operations. This set of tasks would then serve as the primary research vehicle for investigating a variety of issues arising from the use of adaptive systems in the cockpit. In developing this capability, we used the following criteria: (1) the tasks used should be analogous to some of the activities that crewmembers perform during flight; (2) at the same time, the tasks used should be directly related to or have analogs to those studied in the research literature on cognitive psychology and human performance; (3) a balance should be struck between the need for fidelity to real aircraft operations and the need for experimental control over independent, dependent, and extraneous variables, with a bias towards experimental control, at least in the initial stages of the research; (4) the hardware and software requirements for implementing the tasks should be modest, i.e., at the inexpensive, low-end personal-computer level rather than expensive graphics workstations or minicomputers; (5) performance data should be available continuously at experimenter-defined sampling rates for each piloting task; and (6) both non-pilots and pilots should be able to perform the tasks.

On the basis of these criteria, we chose to use the Multi-Attribute Task (MAT) battery, developed by Comstock and Arnegard (1990), as a starting point for the development of our task battery. To meet a number of other requirements of the adaptive automation research program, the MAT software was extensively revised, as described below.

The MAT battery consists of four main tasks that are presented in different windows on the monitor of an AT-class personal computer: tracking, system monitoring, fuel (or resource) management, and ATC communications. Also present are a "scheduling" window showing the beginning and duration of the tracking and communications tasks and a "pump status" window showing the flow rates of the pumps of the fuel management task. All windows are dynamically updated and independent responses are required for each task. Figure 1 shows a typical display of MAT while in operation.


SYSTEM MONITORING
OK
WARNING
TEMP1
PRES1
TEMP2
PRES2
TRACKING
PUMP STATUS
Flow Rates
1 800
2 0
3 800
4 0
5 0
6 0
7 0
8 0
RESOURCE MANAGEMENT
A
B
C
D
2428
2440
951
956
1
2
3
4
5
6
7
8

The four tasks of the MAT meet the above-mentioned criteria to various degrees. For example, with respect to criteria 1 and 2, the tracking (e.g., Wickens, 1986) and monitoring tasks (e.g., Parasuraman, 1986; Wiener, 1984) have analogs in both the aircraft cockpit and the human performance research literature. However, while fuel management and ATC communications are clearly tasks that every pilot performs in the cockpit, these tasks, or analogs of them, have not been systematically studied in the laboratory by experimental psychologists. Nevertheless, the ability to exercise good experimental control and obtain continuous performance data for these tasks, including the performance of nonpilots (criteria 4, 5, and 6), indicates that the lack of an existing body of empirical data and theory for these tasks is not a major drawback. Any such limitation is balanced by the greater realism for aircraft operations that the inclusion of these tasks provides.

In order to meet the special needs of our adaptive automation research program, the MAT software was extensively revised to allow the following features:

¥ Independent script-driven presentation of each of the four tasks. Parameter changes for any task do not require reprogramming or extensive menu selection but simple editing of the relevant task script.

¥ Menu-selectable variation in the presentation and relative positioning of the task windows (e.g., deleting a window or reversing the position of two windows). This feature allows the investigator to examine the effects on performance of task layout and other aspects of the user interface.

¥ Script-driven automation of any task or combination of tasks. This feature was available only for tracking in the original version of MAT but is available for all tasks except ATC communications in the revised version.

¥ Menu-selectable or script-driven variation in the "efficiency" and "reliability" of automation. This feature is unique to the revised MAT. It can be implemented in two versions: (a) automation that is 100% reliable, but has slight "deviations" or "imperfections": i.e. the automation performs the task without error but exhibits slight fluctuations from normal (e.g., an occasional drift of the target in the tracking task to one point of the display without corrective action being applied immediately); (b) automation that is less than 100% reliable. Feature (a) is available for all tasks and feature (b) for the monitoring and fuel management tasks.

¥ Variable performance sampling rates. The rate of sampling operator performance of each task is variable, from a low of every 10 min to a high of every 0.1 sec.

Extensive software development of MAT was carried out in the initial months of the project. An iterative software design procedure was used. Stimulus and task parameters, response modes, and other aspects of the user interface were systematically varied. User tests were then carried out with lab personnel. These informal user performance tests were used as a basis to implement some of the display/interface changes, reject some of the software changes, and revise others. It is anticipated that successive iterations will be required as the requirements for future studies change. The current version of the revised MAT is designed to meet the needs of the experiments to be carried out in the next year of the project.

A key feature of the revised MAT battery is that the component tasks are dynamic. Many laboratory tasks used in human performance tasks appear static; displays are updated intermittently and events are presented discretely. In contrast, the MAT task displays are updated continuously and operator responses are required intermittently. This feature gives the MAT displays very much the "feel" of real-world displays found in the aircraft cockpit or the power plant control room, although the display graphics and symbology are representative of but not exact replicas of any real-world system. This approximation to real displays is combined with the ability to exercise close control over task parameters (such as the timing and frequency of events, the positioning of task information, sampling rate of operator responses, etc), a feature that is normally only characteristic of artificial laboratory tasks.

Descriptions of the four main MAT tasks are presented below. Note that the tasks in the revised/extended MAT differ from those described in the original report by Comstock and Arnegard (1990), particularly for tasks in the automated mode.

Tracking Task

Manual Mode. A first-order, two-dimensional compensatory tracking task with joystick control is presented in one window of the MAT display (see Figure 1). Dashed x- and y- axes are provided for reference. Within the window is a smaller dashed rectangle drawn around the center point of the window. A green circular target symbol, representing the deviation of the aircraft from its course, fluctuates within the window in the x- and y- directions according to a specified forcing function consisting of a sum of nonharmonic sine waves. The highest (cut-off) frequency of the forcing function can be varied; typically 0.05 - 0.1 Hz cut-off frequencies are used in our studies. Control inputs are provide by a displacement joystick. The control dynamics are first-order, or velocity control. If no control input is applied, the aircraft symbol drifts away from the center towards the edges of the window. The subject's task is to keep the aircraft within the central rectangle by applying the appropriate control inputs in the x- and y- directions. For example if the aircraft is to the right of center, a leftward joystick movement will cause the circle to return to the center. Subjects are given training in first-order control by demonstrations of the effects of small and large control inputs (in either the x- or y- directions) on the speed of movement of the aircraft.

Automated Mode. Under automation control, the joystick is disabled and the aircraft movements are compensated for by software. However, small fluctuations around the center of the window remain, to simulate random perturbations in the automatic control. Under normal automated conditions, therefore, the aircraft appears to be anchored at the center of the window, but with very small movements about the center that give the appearance of a dynamic rather than completely static display.

Another automation control option is the appearance of occasional "deviations" in the automatic control. Under these conditions, the aircraft begins to drift from the center until it reaches the inner rectangle and then drifts back. The deviation can be programmed to occur at specified random intervals (or not at all). This option is provided so that the experimenter can simulate the workload associated with operator "supervisory control" of the automation (e.g., Parasuraman et al., 1990; Wiener, 1988). The degree to which the operator "supervises" the automation can then be roughly estimated by querying the operator after the task is completed as to the number of times such deviations occurred. To discourage the operator from continuous, active task processing aimed at detecting such deviations, the deviations should be presented in the form of "catch trials," i.e., the operator should be told that deviations might occur but they should not be presented in every block [2].

Performance Measures. Operator performance of the tracking task is evaluated by sampling the x and y control inputs at 10 Hz and thus deriving the x and y deviations. The root mean square (RMS) error is then computed for the samples obtained over a 1-sec period. In computing the combined horizontal and vertical deviations from the target, vertical deviations are converted (in proportion to the monitor x and y resolution) to horizontal pixel units before combination with the horizontal deviations:

$$\text{RMS error} = \sqrt{\left[\sum_{i}^{N} \{\tilde{x}_i^2 + (K\tilde{y}_i)^2\}/N\right]}$$

where $\tilde{x}$ and $\tilde{y}$ are the x and y deviations, K is the monitor resolution ratio (horizontal/vertical), and N is sample size.

[2] We thank Jonathan Gluckman of NADC for a suggestion that led to the development of this automation option.

RMS error scores for successive 1-sec epochs can also be averaged over a longer time period of performance (e.g., 5 or 10 min) to yield a mean RMS error score for a block.

System Monitoring Task

Manual Mode. The upper left window in Figure 1 presents the system monitoring task. Two monitoring sub-tasks are available, and either or both tasks can be chosen: warning light monitoring and probability monitoring. The warning monitoring sub-task consists of two boxes in the upper half of the window, one green and one red. The light on the left is normally on, as indicated by a lighted green area. The subject is required to detect the absence of this light by pressing the "OK" key on the keyboard when the light goes out. The light on the right is normally off. When the red light comes on, the subject's task is to respond by pressing the "WARNING" key when he or she detects the presence of that red light. If the subject does not detect either abnormality, the situation reverts back to normal status after a preprogrammed timeout period (e.g., 15 seconds).

The probability monitoring sub-task consist of four vertical scales with moving pointers. The scales are marked as indicating the temperature (T1, T2) and pressure (P1, P2) of the two aircraft engines. In the normal condition, the pointers fluctuate around the center of the scale within one limit in each direction from center. Independently and at intervals according to the script, each display's pointer shifts its "center" position away from the middle of the verticle display. The subject is responsible for detecting this shift, regardless of direction, and responding by pressing the corresponding function key (T1, T2, P1, or P2). The appropriate response key is identified below each vertical display.

Feedback is provided when the out-of-range status of a scale is correctly identified by the subject . The pointers of the dial to which the subject responded moves immediately back to the center points and remains there without fluctuating for a period of 1.5 seconds. If the subject fails to detect an abnormality in the probability monitoring task, the fault is automatically corrected 10 seconds from the beginning of its occurrence.

Automated Mode. Under automation control, the keyboard keys T1, T2, P1, and P2 are disabled and the scripted engine malfunctions are identified and responded to by software. To enable the operator to know that the automation has properly detected and corrected the malfunction, an automation "reaction time" of 4 sec is built in. Another automation control option are occasional "deviations" in the efficiency of control, as for the automated tracking task. Under this option, the automation correctly identifies and corrects the malfunction, but has a delayed "reaction time" of 10 sec. The deviations can be scripted to occur at random time intervals. A second automation control option concerns the reliability of the automation. "Automation failures" can be scripted to occur at random time intervals. When such a failure occurs, one of the scale pointers goes out of range. However, the engine malfunction is not detected and corrected by the automation within the 4 sec period. Overall automation reliability is computed as the percentage of malfunctions that are correctly identified by the automation.

Performance Measures. Operator performance for the two monitoring tasks is evaluated by recording all key presses made with the six response keys for the monitoring task. The reaction time associated with a correct response (i.e., to an engine malfunction event) is also computed to within a resolution of 0.1 sec. The percentage of correct detection responses (or hit rate), the percentage of false responses when no malfunction occurs (or false alarm rate), and the mean reaction time for a detection response can be computed from these data. Incorrect detection responses, i.e., when the operator detects a malfunction but presses the wrong key (e.g., presses T1 for a malfunction in the temperature of engine 2) are also recorded, although these tend to be rare. Hit and false alarm rates and mean reaction time are computed for a specified period (e.g., 5 or 10 min) within a block.

Fuel (Resource) Management Task

Manual Mode. This task is meant to simulate the actions need to manage the fuel system of the aircraft. Figure 1 displays the fuel (resource) management window The six rectangular regions are tanks which hold fuel. Levels marked in green within the tanks represent the amount of the fuel in each tank, and these levels increase and decrease as the amount of fuel in a tank changes.

Pumps connect the tanks so that fuel can be transferred from one tank to another in the direction indicated by the corresponding arrow and fuel line. The numbers underneath four of the tanks (Tanks A, B, C, and D) represent the amount of fuel in gallons for each of the tanks. This number is updated every 2 sec as the amount of the fuel in the tanks increases or decreases. The maximum capacity for either Tank A or B is 4000 gallons. Tanks C and D can contain a maximum of 2000 gallons each. The remaining two supply tanks have an unlimited capacity.

Subjects are instructed to maintain the level of fuel in both Tanks A and B at 2500 gallons each. This critical level is indicated graphically by a tick mark in the shaded bar on the side of these two tanks. The numbers under each of these tanks provide another means of feedback for the subject. The shaded region surrounding the tick mark represents acceptable performance. Tanks A and B are depleted of fuel at the rate of 800 gallons per minute. Therefore, in order to maintain the task objective, subjects must transfer fuel from the lower supply tanks.

The process of transferring fuel is accomplished by activating the pumps. Each pump can only transfer fuel in one direction, as indicated by the corresponding arrow. These pumps are turned on when the corresponding number key is pressed by the subject. Pressing the key a second time turns that particular pump off and so on. The pump status is indicated by the color of the square area on each pump. When that area is black, or lacking in color, the pump is off. A green light in this area indicates that the pump is actively transferring fuel.

The flow rates for each pump are presented in the "Pump Status" window. The first column of numbers represents the pump number, one through eight. When a pump is activated, its flow rate is presented next to the pump number in this window. When a pump is off, its flow rate is zero. Pump 1 and 3 transfer fuel at the rate of 800 gallons per min. Pumps 2, 4, 5, and 6 transfer fuel at the rate of 600 gallons per min and Pumps 7 and 8 at 400 gallons per min .

During some sections of the simulation, pump faults occur. This is indicated by the appearance of a red light in the square on the pump. When this occurs, the pump which is in the fault mode is inactive. Fuel cannot be transferred through that pump until the fault is corrected. The operator has no control over the fault correction; the duration of the fault is written into the script that directs the program. When the fault is corrected, the status of that pump is automatically returned to the "off" mode, regardless of its status before the fault condition.

Likewise, when a tank becomes full to capacity, all incoming pumps are automatically turned "off". For example, if all of the pumps were activated and Tank A reached its capacity of 4000 gallons, Pumps 1, 2, and 8 would automatically turn "off". Furthermore, if a tank were to become totally depleted of fuel, all outgoing pumps would be deactivated.

At the onset of each flight simulation, Tanks A and B contain approximately 2500 gallons of fuel each and Tanks C and D contain approximately 1000 gallons of fuel each. All pumps are off at the beginning of the task, leaving all strategic action to the operator's discretion.

Automated Mode. Under automation control, the keys for activating pumps 1 through 8 are disabled. All pump activations are executed from a script that mimics expert performance [3], combined with the following: (1) all fuel level changes are responded to; (2) appropriate pump activations are executed; (2) no "extra" pumps are activated (e.g., activating pump 2 when that has no direct effect on fuel level; this sometimes occurs during manual performance). In addition, two different kinds of pump fault are executed from the script. The first pump failure lasts 60 sec and is similar to pump faults in the manual mode. The second kind of pump failure lasts 90 sec. Under normal automation conditions, only the first kind of pump failure is used. When the

[3] Defined as the performance of two laboratory personnel who had over 30 hours of experience of manual performance on the fuel management task.

experimenter wishes to evaluate the level of operator supervision of the automation, a few additional pump failures of the second type are included in certain "catch blocks". Thus, as is done with the tracking and monitoring tasks, occasional deviations are built into the script. The operator is told that there may be occasional deviations in the time taken to detect and fix pump failures by the automation (90 sec versus 60 sec) and that they may be queried subsequently about the occurrence of such deviations.

Performance Measures. Operator performance on the fuel management task can be evaluated in a number of ways. Detailed records of the key presses that the operator makes are kept so that the particular strategy that the operator uses (if any) to meet task objectives can be ascertained. A global measure of task performance can also be obtained by computing the mean RMS error in the fuel levels of Tanks A and B (deviation from the required level of 2500 gallons). Fuel levels are sampled and RMS error computed over a 30-sec period. RMS error scores for successive periods can also be averaged over a longer time period of performance (e.g., 5 or 10 min) to yield a mean RMS error score for a block. A second global measure of fuel management performance is the number of pump activations per block, although this measure can only be meaningfully interpreted by comparing the operator's strategy to some optimum strategy for performing the task.

ATC Communications Task

Manual Mode. The communications task is presented in the lower left-hand window of the MAT display (see Figure 1). The task consists of a series of audio messages which are presented to the operator through headphones. These messages begin with a six-digit call sign, repeated once, and a command to change the frequency of one of the channels listed on the screen. The operator must discriminate his or her call sign, "NGT504", from other three-letter, three-number combinations. The subject's call sign is always displayed at the top of the communication window. Subjects are required to change navigation and communication frequencies by the use of the arrow keys. The up and down arrow keys are used to select the appropriate navigation or communication radio and the left/right arrow keys increase or decrease the selected radio frequency in increments of 0.2 Mhz.

Automated Mode. This mode is not yet available.

Performance Measures. Operator performance on the communications task is evaluated by computing the mean detection rate, false alarm rate, and reaction time in responding to the aircraft's call sign over a period of time. Reaction time to initiate navigation and frequency changes and errors in making these responses can also be obtained.

Hardware Requirements

The revised MAT battery runs efficiently on any AT-class PC equipped with an EGA video card, although it is preferable to use a 386- or 486-class computer. A Heath voice card and a 8088-class PC are also needed for the ATC communications task. Accessories needed include a joystick and I/O card for the tracking task and a pair of earphones for the communications task.

PILOT STUDY

The pilot study was carried out to "calibrate" the first-order tracking task so that an appropriate level of difficulty could be established for use in subsequent studies of multiple-task performance and in the adaptive-automation studies. Pilot data was already available on the performance characteristics of all four tasks of the MAT (Comstock and Pope, personal communication). However, performance data for the tracking task had been gathered using a mouse as a control device, which we felt was not the most appropriate control input for a tracking task meant to simulate flight operations. We therefore performed a pilot study examining the performance characteristics of the tracking task using both a mouse and a joystick as control devices.

Subjects

Twelve volunteers drawn from the staff of the Cognitive Science Laboratory and the Department of Psychology, six males and six females, participated in a single session lasting about 45 minutes. They ranged in age from 22 to 35 years, were right-handed, and had normal (20/20) or corrected-to-normal vision. None of the subjects had prior experience with the MAT tasks.

Procedure

The revised MAT was used with the tracking window active under the manual mode. The 12 subjects were allocated randomly to two equal groups of six subjects each with the restriction that the groups be matched for gender. One group used the mouse as a control device while the other group used the joystick. Each subject was tested in two phases consisting of several blocks of 5 min each. In the first phase, following instruction and training, the tracking task was performed at each of three levels of difficulty, defined in terms of the highest (cutoff) frequency of the forcing function, as follows: .016 Hz (easy), .064 Hz (moderate), and .112 Hz (difficult). Within each group (mouse or joystick), three of the subjects tracked in the order easy--moderate--difficult, while three tracked in the reverse order. After a short rest break, subjects performed three successive 5-min blocks of the tracking task (with short rest breaks) at the moderate level of difficulty, in order to assess the effects of modest levels of practice on tracking performance using a mouse or a joystick.

Results

Preliminary analysis of the data revealed no effect due to subject gender. The results of all subsequent analyses are for data collapsed across gender.

The mean root mean square (RMS) error in the x- and y- directions was computed (in adjusted pixel units; see previous section on revised MAT battery for the formula used for computing RMS error) for each 5-min block of the tracking task. These data were submitted to an analysis of variance (ANOVA) with control device (mouse/joystick) and testing order as between-subjects factors and forcing function frequency (difficulty level) as a within-subjects factor. A second ANOVA of RMS error scores was also carried out for the moderate-difficulty condition, with control device as a between-subjects factor and blocks as a within-subjects factor.

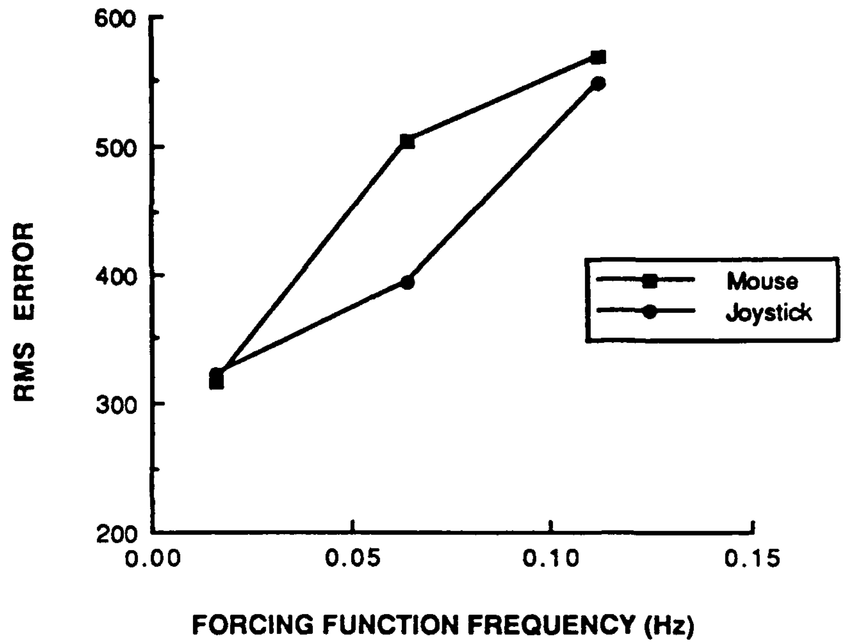


Figure 2. Effects of forcing function frequency (tracking difficulty) on mean RMS tracking error.

Figure 2 shows the mean root mean square (RMS) error in the tracking task for each control input as a function of task difficulty (forcing function frequency). RMS error increased with forcing function frequency, $F(2,16) = 6.35$, $p < .01$, confirming that the effect of task difficulty on performance was reliable. The main effect of control device was not significant, indicating that performance was equivalent for the mouse and joystick. The effects of testing order and all interactions were not significant.

Figure 3 shows mean RMS error scores for each control device for the moderate difficulty tracking condition as a function of blocks of practice. ANOVA of these data gave no significant effects. We anticipated that RMS error would decline with practice at tracking. Somewhat surprisingly, however, RMS error did not change significantly with blocks of practice. This could have occurred because subjects may have reached asymptotic levels of performance in the earlier phase of the experiment in which they performed the tracking task at all three levels of task difficulty.

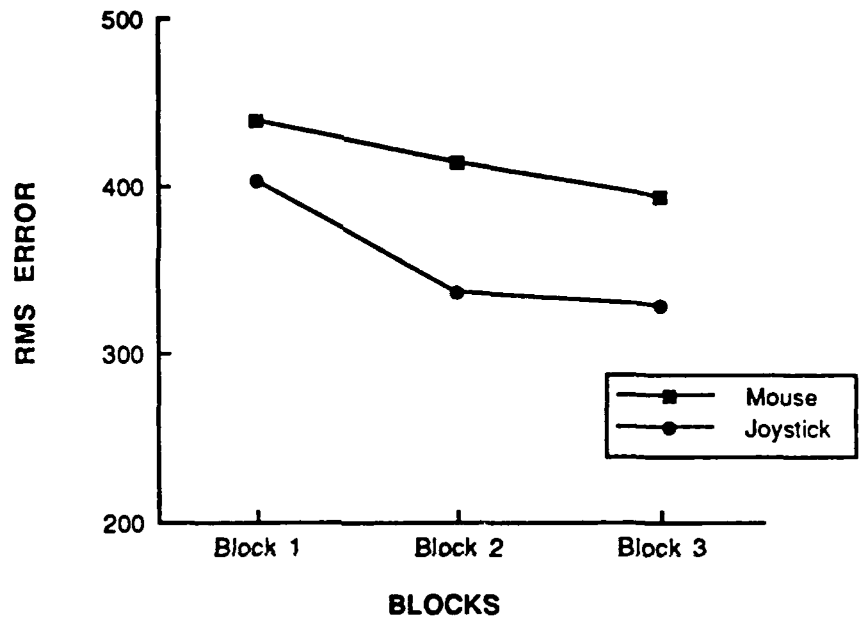


Figure 3. Effects of practice on tracking performance.

Discussion

The present results confirmed the sensitivity of the tracking task to changes in task difficulty as manipulated by variations in the forcing function frequency. Furthermore, tracking performance was relatively insensitive to practice effects, although as discussed earlier this might have occurred because subjects reached their personal performance ceilings in prior practice. Whatever the cause, the results indicate that for the present tracking task, only a modest amount of practice is needed for performance with either the mouse or joystick to reach relatively stable levels.

On the basis of these results, we chose the .064 Hz forcing function frequency, representing the moderate difficulty condition, as the baseline tracking difficulty level for subsequent studies. By choosing this frequency one could be confident that either a decrease or an increase in forcing function frequency (as might occur under conditions in which adaptive automation is invoked) would result in appropriate changes in performance levels. The results also suggest that extensive practice is not required to reach stable performance levels on the tracking task. Finally, satisfactory results were obtained with either the mouse or the joystick control. However, the joystick was chosen over the mouse for subsequent studies because of its closer relation to cockpit control devices and because subjects reported finding the joystick easier to use.

MULTI-TASK PERFORMANCE CHARACTERISTICS

The pilot study established an appropriate task difficulty level for the tracking task. As mentioned earlier, task parameters required to attain particular performance levels for the monitoring, fuel management, and ATC communications tasks were known. However, for each of these tasks, performance levels were obtained for single-task conditions; efficiency levels for dual-task and multi-task performance were unknown. The present study was designed to obtain performance data in these conditions. Only three tasks were used, tracking, monitoring, and fuel management. The hardware required to run the communications task was not available at the time of this study. However, this task is now in operation and can be used in future studies.

Subjects

Eight students from The Catholic University of America, 4 males and 4 females, participated to fulfill a course requirement. Each subject was tested in a single 2-hour session. Subjects ranged in age between 18 to 25 years. All subjects were right-handed and had normal (20/20) or corrected-to-normal vision. To avoid any previous learning effects, all participants had never been subjects in similar experiments before.

Procedure

The revised MAT was used with the tracking, monitoring, and fuel management windows active in the manual mode. Each subject performed in each of seven task combination conditions: the three tasks (T = tracking; M = monitoring; F = fuel management) alone, the three combinations of pairs of tasks (TM, TF, and MF), and the multi-task condition (TMF) [4]. Half the subjects performed the tasks in an order progressing from single through dual to multi-tasks: T-M-F-TM-TF-MF-TMF; while the other half did the tasks in the reverse order: TMF-MF-TF-TM-F-M-T.

Following instructions and training each subject performed for seven 10 min-blocks, one for each of the seven task combination conditions. Subjects were shown their results and were given feedback regarding their performance at the end of each block. In the dual-task and multi-task conditions, subjects were instructed to given equal priority to each task.

Results

Preliminary analysis of the data revealed no effects due to operator gender and hence the data were collapsed across this subject variable in all subsequent analyses. Figure 4 shows mean RMS error for the tracking task as a function of task combinations. Tracking was relatively efficient when carried out in isolation but became poorer with the introduction of the other tasks. The RMS data were submitted to an ANOVA with order of testing as a between-groups factor and task combinations as a within-groups factor. ANOVA showed that RMS error varied significantly with task combinations, $F(3,18) = 7.01$, $p < .01$, but not with order or with the interaction of order and task combination. Figure 4 indicates that tracking error increased markedly in the

[4] In all conditions, only the relevant task windows were displayed. For example, in the dual-task tracking and monitoring condition, only these two windows were active; the fuel management (as well as pump status) windows were empty.

	TM	TF	TMF
T	133.6*	205.3*	205.6*
TM		71.7	72.0
TF			0.3

* $p < .05$.

Table 1. Differences in tracking RMS error between different task combinations (T = tracking; M = monitoring; F = fuel management).

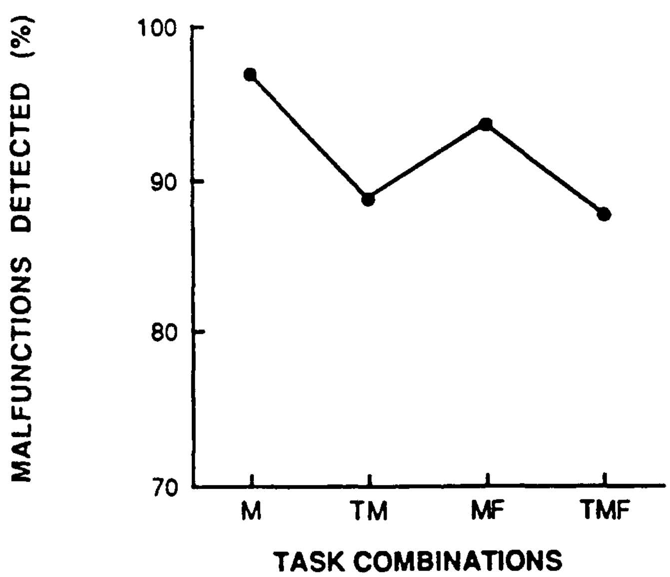


Figure 5. Accuracy of monitoring performance as a function of single-, dual-, and multi-task conditions. (M = monitoring; T = tracking; F = fuel management).

Monitoring accuracy (rate of correct identification of engine malfunctions) under single and multi-task conditions is shown in Figure 5. When performed alone, performance accuracy was very close to 100%. Monitoring accuracy was reduced when performed with the tracking and fuel management tasks, and further reduced when all three tasks were performed. But although there was a trend towards performance reduction with task combination, the effect of conditions was not significant, $F(3,18) < 1$. The ceiling levels of single- and dual-task performance (over 93%) *preclude statistical analyses of these data.*

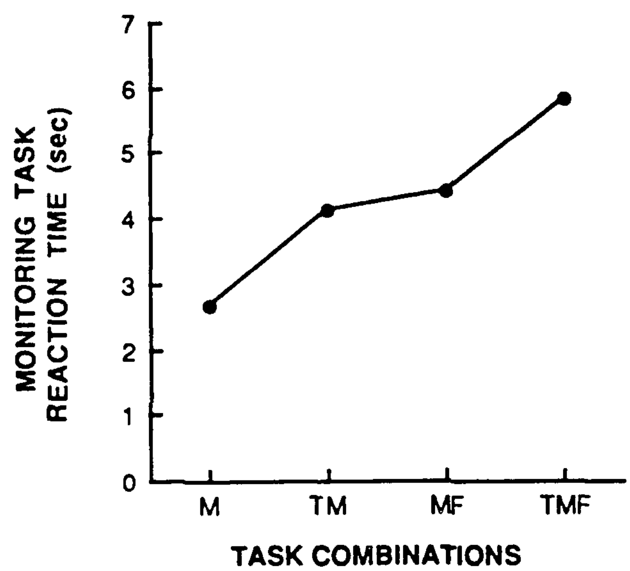


Figure 6. Mean monitoring task reaction time as a function of single-, dual-, and multi-task conditions. (M = monitoring; T = tracking; F = fuel management).

Mean reaction time in the monitoring task is displayed in Figure 6. An almost linear increase in RT occurred with task combinations, an increase that was significant by ANOVA, $F(3,18) = 10.01$, $p < .001$. The effects of testing order and the order x task combination interaction were not significant. The significance of differences between ordered means for the different task combinations were carried out using the Newman-Keuls test, as was done for the tracking task. Table 2 gives the mean differences in reaction time between all possible task combinations. Again, as for the monitoring task analysis, five contrasts were expected to be reliable. Table 2 shows that four of these contrasts were significant. The fifth, comparing the monitoring/fuel management condition with the multi-task condition, was of borderline significance.

	TM	MF	TMF
M	1.47*	1.75*	1.67*
TM		0.28	1.69*
MF			1.41/

* $p < .05$.
/ $p < .07$.

Table 2. Differences in monitoring task reaction time (in sec) between different task combinations (T = tracking; M = monitoring; F = fuel management).

Taken together with the results for monitoring accuracy, these results indicate that monitoring performance was sensitive to task combination, but that speed of monitoring declined more markedly than accuracy as the tracking and fuel management tasks were added to the monitoring task.

Performance on the fuel management task is shown in Figure 7. This figure indicates an increase in RMS error in setting fuel levels with task combination. Although mean RMS appears to increase markedly with task combination, there was very high inter-subject variability for this measure of fuel management performance, and the effect of conditions was not significant, $F(3,18) < 1$, but the order by conditions interaction was significant, $F(3,18) = 4.32$, $p = .05$. The interaction came about because the subjects who performed the single-task condition first had extremely high RMS error scores, which led to a weakening of the effect of task combination, whereas subjects performing the tasks in the reverse order showed the expected increase in RMS error as a function of task combination. The unusually high initial single-task RMS error, which may have resulted from insufficient practice at the task for these subjects, coupled with the very high inter-subject variability in this measure, contributed to the lack of significance of the main effect for task combination conditions.

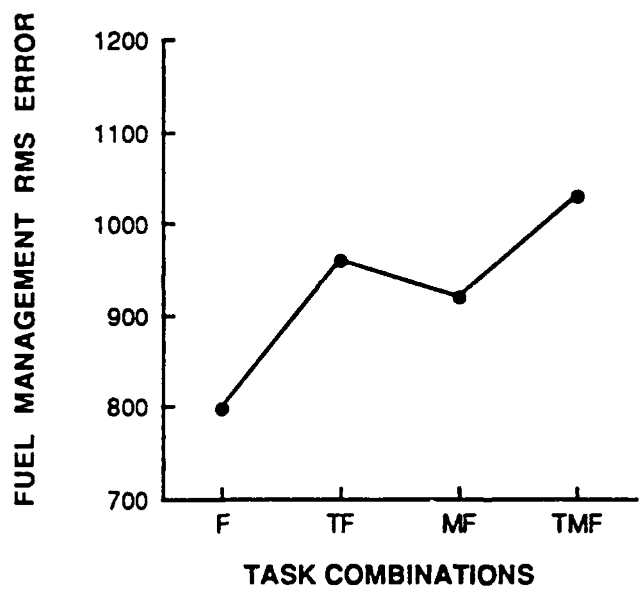


Figure 7. Fuel management performance as a function of single-, dual-, and multi-task conditions. (F = fuel management; T = tracking; M = monitoring).

Discussion

The results of the present study point to a fairly regular pattern of performance changes on each task in response to concurrent task demand. Both the tracking and monitoring tasks showed the anticipated performance decrements from single- to multi-task performance (Wickens, 1987). These performance decrements were in the expected direction and were systematic: for the tracking task, three out of the five possible contrasts between different task pairings (i.e., single-dual and dual-multi) gave reliable evidence of performance decrement, whereas for the monitoring task (reaction time measure), four out the five comparisons were statistically significant. Given the relatively small sample size of this study, these results are encouraging, and indicate that both the tracking and monitoring tasks of the revised MAT battery are sufficiently sensitive to variations in task load and should therefore be appropriate for our future studies of adaptive automation in which task difficulty and task load will vary dynamically.

While both the tracking and monitoring tasks were highly sensitive to concurrent task load, there was an interesting dissociation between the tasks at the highest level of load. Tracking performance decreased significantly from single-task performance to both dual-task loadings (tracking/monitoring and tracking/fuel management). However, the performance decrement from dual-task to multi-task loadings was much reduced, and in fact was significant for only one of the two such contrasts (see Figure 4). On the other hand, the monitoring task showed consistent decreases in performance from single-task to dual-task to multi-task loadings. This might have resulted from the operators using a strategy of "protecting" performance on the tracking task under the highest levels of load (e.g., Wickens, 1987). Although operators were told that the tracking and monitoring tasks had equal priority, they may have perceived the tracking task as being more important and allocated additional resources to perform this task when all three tasks had to be performed concurrently. In contrast, the monitoring and fuel-management tasks may have been perceived as of secondary importance; and in fact performance on these tasks did decrease in the multi-task condition (although significantly so only for the monitoring task).

While tracking and monitoring performance changed consistently with concurrent task demand, performance on the fuel-management task was less consistent. Inspection of the mean performance scores showed some indication of decrement under concurrent load, i.e., from single-task to dual-task and from dual-task to multi-task combinations, but the particular performance measure that we chose, fuel-management RMS error, was highly variable, and was not affected significantly by task load. Nevertheless, the fuel-management task did have an impact on multi-task performance, as evidenced by performance decrements on the monitoring and tracking tasks when it was paired singly or jointly with these tasks. Thus, the task did clearly contribute to the overall processing demand imposed on the operator. Automation of this task should therefore have an impact on operator performance of other tasks in an adaptive automation environment. From this (admittedly limited) perspective, we concluded that the fuel-management task would be useful in our future adaptive automation studies, although the lack of sensitivity of the task itself is problematic and will require additional work to resolve.

Why was the fuel-management task not sensitive to task load? There are several possibilities. First, the measure we chose may not have been the best one. As mentioned earlier, there was very high inter-subject variability in this performance measure. In Wickens' (1984) terms, this measure was not *sensitive to* operator workload experienced in performing this task. We are currently exploring other ways of characterizing performance on this task. Second, the fuel-management task may have been more sensitive to practice effects than the other two tasks. (In our pilot study we investigated practice effects only for the tracking task). At least for the RMS error measure, there was evidence of practice effects lasting well into the experimental session. These practice effects may have masked the effects of task loading. Third, of all the tasks in the MAT, the fuel management task is the one that allows the operator the greatest flexibilty in the way the task is performed. This implies that subjects probably used a variety of different strategies to perform the task. This in turn could have contributed to the variability in the RMS error measure. Unfortunately, we do not currently have a way of assessing what strategies were used. (Informal questioning of the subjects did not provide any reliable information as to strategies used.) This is clearly a point for future research to pursue, particularly in the context of adaptive automation. Automation may change the way that operators perform tasks, particularly if they are switched rapidly from manual to automated modes and back, as is possible in an adaptive automation environment (Parasuraman et al. , 1990). Such strategy changes need to be better understood in order to evaluate the impact of adaptive automation on operator performance.

Finally, from a purely theoretical perspective, the present results provide no information on the source of task interference in multi-task performance (e.g., Gopher, 1986; Kahneman, 1973; Navon, 1984; Wickens, 1987). The performance profiles obtained in the present are consistent with operator limitations in perceptual/cognitive processing resources or in structural factors (Kahneman, 1973). The latter refers to interference at the input stage, for example because of the inability of the operator to fixate two display locations at the same time, or to output interference, for example because the same motor pathway has to be used to execute responses to two tasks. (See also Navon, 1984, for additional descriptions of input and output sources of interference).

It can be argued that resource scarcity rather than structural interference was the major source of performance decrement in the present study. At the input end, all display windows were capable of being processed without the need for peripheral vision. If the operator fixated the center of the tracking window, for example, then the monitoring and fuel management windows were within 6^{o} of visual angle. Subjects clearly did make eye movements to different task windows; and there is evidence that information is processed less efficiently at non-attended locations than at attended locations (Posner, 1980). However, there was no consistent evidence that subjects fixated or visually attended to one display window to the exclusion of others (with the possible exception of the tracking task in the multi-task condition, where, as mentioned perviously, subjects may have attended more to the tracking window in order to maintain performance under increased load).

With respect to the output stage of information processing, the input controls for the different tasks were clearly defined and separated, and were consistent with high stimulus-response compatibility, all of which should reduce the likelihood of output interference (Navon, 1984). The tracking task was performed with the right hand, and the monitoring and fuel management tasks with the left hand. While the same motor pathway was used for the latter two tasks, operators were rarely required to execute responses to the two tasks simultaneously. On the rare occasions when both tasks required action at about the same time, output interference was again likely to be low because the fuel-management task was not a reaction-time task, and it could be responded to following the monitoring response without a significant impact on performance.

Whatever the precise theoretical reasons for the pattern of performance decrement obtained (and the present study was not designed to distinguish between these alternatives), the results show that the revised MAT tasks were sufficiently diagnostic of concurrent task demand on the operator. Taken together with the data from the pilot study, the results established the sensitivity of the tracking, monitoring, and fuel management tasks of the revised MAT battery to variations in task difficulty and task load. As such, the present study met its objective of providing a baseline for further studies of adpative automation in which task difficulty and task load will be varied dynamically.

CONCLUSIONS

The three studies conducted as part of our initial investigation on the effects of adaptive automation were successful in meeting most of the start-up goals of our research program. The first study resulted in test software--the revised Multi-Attribute Task battery--that will provide the platform for examining performance effects of adaptive automation. These results of the second and third studies established a baseline of empirical performance data in a multi-task flight-simulation environment. These data will help in the design and interpretation of results of future adaptive-automation studies that will be carried out as part of this research program.

REFERENCES

Chambers, N. & Nagel, D. C. (1985). Pilots of the future: Human or computer? *Communications of the ACM, 28,* 1187-1199.

Comstock, J. R., & Arnegard, R. J. (1990). *Multi-attribute task battery.* Technical Report (in progress). NASA Langley Research Center, Hampton, VA.

Fuld, R. B., Liu, Y. and Wickens C. D. (1987). The impact of automation on error detection: Some results from a visual discrimination task. *Proceedings of the Human Factors Society*, 31st Annual Meeting 156-160.

Gopher, D. (1986). In defense of resources. In G. R. J. Hockey, A. Gaillard, & M. G. H. Coles (Eds.) *Energetics and human information processing.* Amsterdam: Nijhoff.

Hancock, P. A., Chignell, M. H., & Lowenthal, A. (1985). An adaptive human-machine system. *Proceedings of the IEEE Conference on Systems, Man, and Cybernetics, 15,* 627-629.

Hart, S. G. & Sheridan, T. (1984). Pilot workload, performance, and aircraft control automation. In *NATO/AGARD Symposium on High Performance Aircraft* (pp. 183-188). Williamsburg, VA: NATO/AGARD.

Idaszak, J. R., and Hulin C. L. (1989). *Active participation in highly automated systems: Turning the wrong stuff into the right stuff.* Technical Report, Aviation Research Laboratory. Institute of Aviation, University of Illlinois at Urbana Champaign.

Kahneman, D. (1973). *Attention and effort.* Englewood-Cliffs, NJ: Prentice Hall.

Kibbe, M. P. and Wilson, S. B. (1989). *Information transfer from intelligent EW displays.* Technical Report. Naval Weapons Center, China Lake, CA.

NASA (1989). *Aviation safety automation: A plan for the research initiative.* Washington DC: Office of Aeronautics and Space Technology, NASA.

Navon, D. (1984). Resources: A theoretical soup stone. *Psychological Review, 91*, 216-234.

Noah, W., & Halpin, S. M. (1986). Adaptive user interfaces for planning and decision aids in C^3I systems. *IEEE Transactions on Systems, Man, and Cybernetics, SMC-16*, 909-918.

Parasuraman, R. (1986). Vigilance, monitoring, and search. In K. Boff, L. Kaufman, & J. Thomas (Eds.) *Handbook of perception and human performance. Volume 2: Cognitive processes and performance.* New York: Wiley.

Parasuraman, R. (1987). Human-computer monitoring. *Human Factors, 29,* 695-706.

Parasuraman, R., Bahri, T., Deaton, J. E., Morrison, J. G., & Barnes, M. (1990). *Theory and design of adaptive automation in aviation systems.* Warminster, PA: Naval Air Development Center (Code 6021).

Parasuraman, R. & Bowers, J. C. (1987). Attention and vigilance in human-computer interaction. In A. Gale & B. Christie (Eds.) *Psychophysiology of the Electronic Workplace.* (pp. 163-194). London: Wiley.

Posner, M. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32*, 3-25.

Rouse, W. B. (1976). Adaptive allocation of decision making responsibility between supervisor and computer. In T. B. Sheridan and G. Johannsen (Eds.) *Monitoring behavior and supervisory control.* New York: Plenum Press.

Rouse, W. B. (1988) Adaptive aiding for human/computer control. *Human Factors, 30*, 431-438.

Wickens, C. D. (1984). Processing resources in attention. In R. Parasuraman & D. R. Davies (Eds.) *Varieties of attention.* Orlando: Academic Press.

Wickens, C. D. (1986). The effects of control dynamics on performance. In K. Boff, L. Kaufman, & J. Thomas (Eds.) *Handbook of perception and human performance. Volume 2: Cognitive processes and performance.* New York: Wiley.

Wickens, C. D. (1987). Attention. In P. A. Hancock (Ed.) *Human factors psychology.* Amsterdam: Elsevier.

Wickens, C. D. & Kessel. C. (1981). Failure detection in dynamic systems. In J. Rasmussen and W. B Rouse (Eds), *Human detection and diagnosis of system failures.* New York: Plenum.

Wiener, E. L. (1984). Vigilance and inspection. In J. S. Warm (Ed.) *Sustained attention in human performance.* London: Wiley.

Wiener, E. L. (1988). Cockpit automation. In E. L. Wiener & D. C. Nagel (Eds.) *Human factors in aviation.* San Diego: Academic Press.

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