Procedure and Dynamic Display Relocation on Performance in a Multitask Environment

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***Abstract*—In this paper, the responses of experienced professional pilots to change in interface configuration and differing automated invocation procedures were examined using a simulated flight-task environment. Performance was evaluated on three subtasks: two-dimensional compensatory tracking; fuel management; and systems monitoring. The status of automation, which was available for tracking and fuel management only, was conveyed by a change in display configuration represented by either a reduction in the size of the relevant display or by a reduction in size accompanied by its displacement to a peripheral spatial location. Combined with these interface-configuration changes were two forms of automation invocation procedure, which were pilot-initiated automation and system-initiated automation. Each was compared to a standard manual-control condition. Results indicated several response asymmetries. While tracking showed no effect for the location of the automated fuel-management display, fuel-management performance did reveal a significant effect, which favored the peripheral location of the automated tracking display. This display-location effect is thought to result from a general requirement for pilots to change their visual-scan pattern. The converse effect does not appear for fuel management and represents the continued primacy given by the pilots to tracking performance. System-initiated automation of fuel management, as a set condition, resulted in significantly better tracking performance, in both mean and variability measures, when compared to pilot-initiated automation. In the converse situation, involving the automation of the tracking subtask, a significant difference was also evident, but only in the variance measure of the fuel-management performance. The fuel-management variance for the pilot-initiated automation of tracking was significantly lower than that for the condition where the automation was enacted by the system. These results indicate that the automation-initiation process itself influences subsequent multitask performance. The present results support a general contention that the operator should initiate automation, except in circumstances in which the operator is for some reason incapacitated.**

***Index Terms*—Adaptive-task allocation, automation, displays, dynamic-interface configuration, multitasking, perceived workload.**

I. INTRODUCTION

HIGH TASK demand and high-stress conditions are regularly seen in the operations of many complex technical systems. Often, these "moments of terror" are interspersed among "hours of boredom" [1]. The resulting fluctuation in demand places an insupportable load on operators during emergencies, while conversely reducing load to a minimum when demands are already toward their lowest level. Surprisingly, these latter underload conditions can prove as stressful to the sensation-seeking human operator as their overload counterpart [2]. Nowhere is this fluctuation in demand encountered more frequently, or more radically, than in the operations of advanced aircraft [3]–[5]. As the modal environment, in which demand fluctuation is evident, this paper uses a simulation of these flight-representative tasks. However, the principles derived from this paper are clearly relevant to the operations of many other complex technical systems in which radical changes of workload are evident.

To reduce the performance impact associated with these radical fluctuations in demand, we need to enact more than just a one-time discrete task-allocation division between operator and machine [6], [7]. We need the ability to switch, transfer, relieve, merge, and enjoin task demands upon a moment's notice according to the immediate operational necessities. Such requirements mandate a cooperative procedure in which the operator and system dynamically complement each other in accomplishing the necessary tasks [8], [9]. Consequently, automation can no longer remain a simple binary alternative to manual control [10]. Rather, automation must share in responding to overall demand, and as a general design strategy, automation should adapt to the changes in human capacity that occur during the various phases of operation [11], [12].

Adaptive automation [13]–[16] is a strong and viable alternative to the static automation policies of the past. Adaptive automation, which is designed to regulate task loading, is capable of engaging and disengaging in response to a variety of specific conditions. These conditions include, but are not limited to: 1) the occurrence of critical events; 2) the performance level of operators themselves; or 3) the violations of a preagreed performance envelope. More generally, adaptive automation is responsive to context, and there are four fundamental categories of these contextual triggers. A first triggering context may be specified by events or conditions in the environment. However, sensing all the properties of the ambient environment that are related to the performance of the operator and the system is extremely difficult because of the explosion of combinatorial factors involved. Thus, while some environmental information will always remain critical, it is unlikely that we can, or even should, develop adaptive automation founded upon environmental sensing alone.

A second contextual trigger for adaptive automation may be specified by the system itself. At the present time, this

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approach is the one that is most developed because of the extensive investment by the manufacturers in providing real-time information about the momentary performance of the systems that they fabricate. In this way, the trigger for automation is a function of the performance limitations of the system itself. For example, certain envelope restrictions such as recovery from stall warnings are already in a number of contemporary aircraft and this works well for the normative conditions of commercial transportation. However, in more demanding operations, where the performance boundaries are not always as easily defined, initiating automation based on aircraft condition may remove control from the pilot at exactly the point in time where manual control is most critical.

The third contextual trigger is based upon information about the state of the operator. In this circumstance, change in automation depends upon the assessment of the human's response capacity. Flight performance itself can be taken directly as one critical metric of pilot state, but other relevant measures include psycho-physiological assessment, performance modeling, critical-event logic, and subjective report among others [14], [17]. When the pilot's limits are exceeded, then the tasks need to be reallocated just as flight controls need to be adjusted when the aircraft exceeds a safe operational envelope. A classic case of automation take-over initiated by pilot incapacity is the case of gravity-induced loss of consciousness.

The fourth and final contextual trigger is the hybrid case. This is the one in which the elements of pilot state, aircraft state, and environmental conditions are each used in either pairwise or overall combination to determine the initiation of adaptive automation. It will come as no surprise that while different strategies may feature information from one of the three main elements, to a greater or lesser degree, it is almost inevitable that the hybrid contextual trigger is one toward which all advanced design architectures are moving. Pragmatically, we are already gathering large amounts of information about system conditions and the immediate ambient environment. More than enough information, for example about current aircraft state, is already roiling about the vehicle. Moreover, with the advances in the behavioral and neurosciences, we are understanding more and more about the human operator and how to integrate the information about them to generate coherent systems operation [18], [19]. Thus, understanding the temporal triggering of adaptive automation has made important progress.

Despite this evident progress in understanding *when* automation may be triggered, we still have much to learn about *what* in the overall task assemblage should be automated and *how* that automation process should proceed. Thus, to take the research in adaptive automation a step further, we need to consider *adaptive function allocation* as mediated through an arbitration mechanism such as an intelligent interface [13]. The question of adaptive function allocation has become the subject of a strategic program of empirical attack [20]–[22]. Adaptive function allocation focuses on the issues of what task components are automated and what are left with the operator and, furthermore, it focuses on how the hand-over of control is achieved [23].

Thus, adaptive function allocation seeks global goals like the improvement of operator situation awareness, maintenance of task involvement, regulation of workload, enhancement of monitoring or vigilance, and the maintenance of manual-skill levels [24], [25]. These issues, of course, remain of concern to many contemporary operators of static automation. Empirical evaluation of the validity of these global claims has already been set in progress [26]–[29]. However, much of the research concerning adaptive function allocation has been in regard only to these global concerns. Very little work has focused upon exactly how displays need to be structured to optimize performance or what mode of control transfer proves superior for momentary performance and for later recovery of manual control. The primary purpose of the present investigation is to evaluate the effects of such interface structures and automation invocation procedures in combination.

There is no mathematical prescription that frames interface design [30]. In the aviation environment, interfaces have been the subject of much computational and psychological inquiry [31]. The move from analog to digital displays has been accompanied by the parallel integration of computer mediation [32]. For example, the computer systems continuously adjust pilot stick inputs in digital fly-by-wire aircraft while calculating and creating predictive flight-path displays, while protecting against pilot errors (e.g., stall configurations). The computer acts as a go-between for the pilot–vehicle interface. Consequently, contemporary displays are distinctively different from those of earlier aircraft. However, the function of displays remains fundamentally the same; that is, the communication of aircraft and environmental status to the pilot to maintain and promote safe and efficient operation.

Regrettably, displays in the contemporary cockpit do not always fulfill this function. Detection of remote-system failures has sometimes been attributed to display structure as a proximal cause in aircraft incidents and crashes [33], [34]. The demands of contemporary flight, the time constraints in particular, mean that proliferation of older type displays is not the solution but in fact is part of the problem. As the aircraft systems become more advanced, more information is required by the pilot in order to fly the aircraft efficiently. However, the pilot must integrate that information in order to perform this task. The older type displays and additions of similar displays may inhibit the pilot in this process of integration. Merely proliferating displays and hiding many "behind" CRT screens are also not a solution, although some surface simplification may appear to have occurred. In terms of attentional resources, the integration of information implies the necessity for integrated displays [35]. An example of an integrated display in a current cockpit is the horizontal-situation indicator (HSI). This display integrates the information from the VOR, the very high-frequency omnirange indicator and the DG, the directional gyro. Both are instruments required in completing the task of navigating the aircraft. The HSI therefore "simplifies" this task for the pilot.

The question is how to bring relevant information to the pilots' attention at the relevant time, a task which also includes the suppression of distracting information. Offloading requires changes in display characteristics that react either to pilot command or some other trigger, predicated upon current and expected performance state. The display characteristics change either at the discretion of the pilot's inputs or the system's status alterations. Hence, interface configuration is intimately associated with how control is exercised not only for automation invocation itself but also the control of the information presentation. Therefore, adaptive automation is based on the rationale that performance may be optimized by managing the flow of information via display presentation and task demands via onset and offset of automation of one or more tasks so that the operators' resources are appropriately allocated continuously over time.

There has been a previous examination of this problem of interface structure in conjunction with automation invocation procedures using flight-naive participants [20]. While these data are of interest, we need much more information on the response of professional pilots who use and manipulate such information on an every day basis. Consequently, this paper builds upon this earlier work but, here, examines the responses of a group of experienced pilots as participants.

II. EXPERIMENTAL METHOD

A. *Experimental Participants*

To test the experimental propositions, ten experienced male pilots volunteered to participate. Their mean age was 38.7 years with a range from 28 to 49 years of age. Their average flight hours were 7174 with a range from 180 to 16 000 h. Of the ten pilots, six had previous military-fight experience and their present aircraft ranged from a Boeing 747, Boeing 757, to a DC-9. All participants were in professed good health at the time of testing and none received any external remuneration for their participation.

B. *MINSTAR Test Facility*

Pilot performance was evaluated using the MINnesota Systems Task Allocation Research (MINSTAR) test facility. MINSTAR is a synthetic multitask environment capable of assessing the simultaneous performance of tracking, fuel management, monitoring, decision making, and cognitive workload [36]. A photograph of the MINSTAR display, given in Fig. 1 and represented schematically in Fig. 2, shows the tracking, monitoring, fuel-management, and psychological-assessment tasks. These tasks were selected to assess the participant's ability to meet task demands that are present in the operational environment of an advanced single-seat high-performance aircraft.

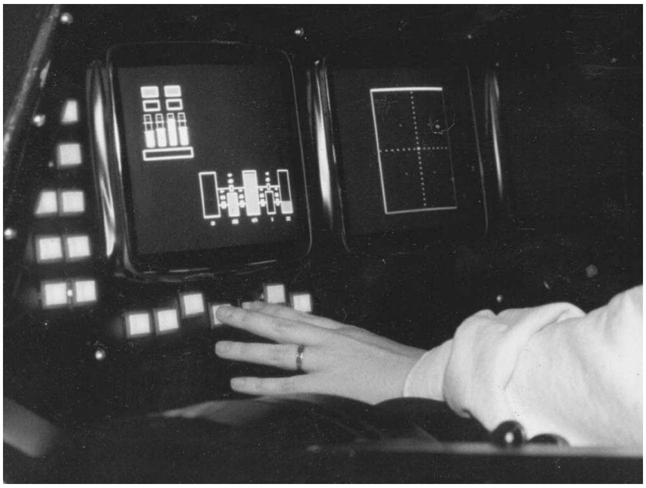


Fig. 1. Photograph of the MINSTAR test facility. On the CRT to the left, the monitoring task appears (composed of both gauge and light monitoring at upper left on the CRT) and fuel-management subtasks. On the CRT, to the right, is the tracking task. Note that all subtasks are currently in the manual mode of operation. As no SWAT response is presently required, the Message window, which when active is shown directly below the monitoring task, does not presently appear. When active, it appears in the location shown schematically in Fig. 2.

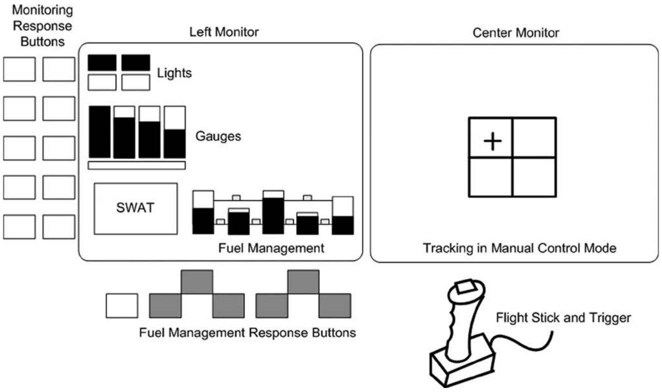
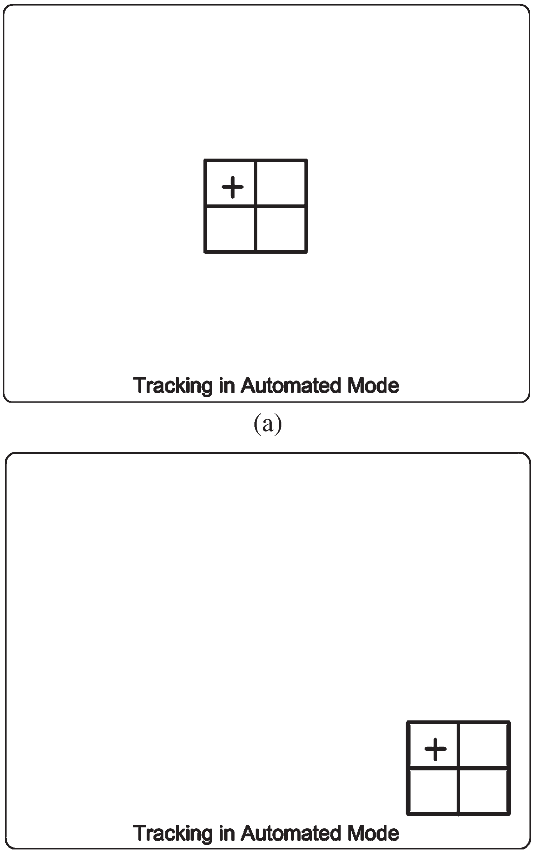


Fig. 2. MINSTAR display showing left and right CRTs and the location of subtasks and response buttons. The arrangement of the fuel-management response-button maps to the pump arrangement shown on the left CRT. The response button to the left of the fuel-management buttons was used to initiate and negate automation of the fuel-management subtask. The monitoring response buttons, also mapped to the lights and gauges, were positioned to the left of the left CRT. The control for tracking automation was located on the flight stick. SWAT assessment was presented in the message window, below monitoring gauges, labeled SWAT on the left CRT.

1) Tracking Task: Tracking is the subtask that provides a continuous demand on the participant. It is the analog for either vehicle (aircraft) control or continuous-process modulation in the MINSTAR facility. Under most performance conditions, tracking provides the major source of momentary load. In the future, therefore, when adaptive allocation is more widely implemented, it is likely that this continuous demand task will become the major candidate for offload and, thus, exhibit the greatest performance benefits from adaptive automation. In the present configuration, tracking appears in the central display. MINSTAR employs a two-dimensional compensatory tracking task, in which the participant is required to center crosshairs/cursor using a flight stick (see Figs. 1 and 2). The aircraft's x and y coordinates are each varied by the sum of seven sine waves of different phase and amplitude. Flight-stick manipulation is required to maintain the desired central position. Further specific details as to this particular task have been recently reported [37]. Participant's performance on this task is assessed by measuring the deviation of the target from the desired center position. The difficulty of this task was increased in consistent increments at the end of each minute of each 10-min trial. This was done so that the pilot would eventually "need" automation to control the task in order to maintain successful overall performance. The two variations of the display for the automated modes are shown in Fig. 3(a) for the central location and Fig. 3(b) for the peripheral location.



(a)

(b)

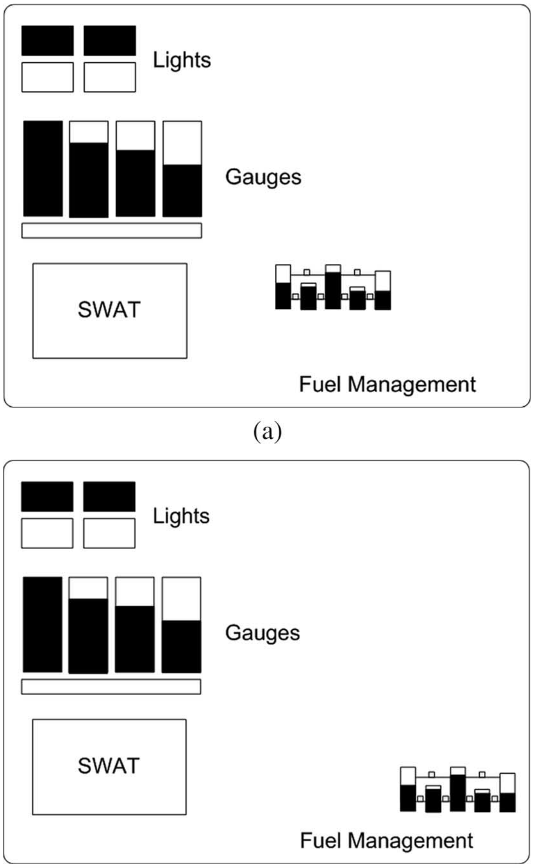
Fig. 3. (a) Tracking display in automated mode, placed in the central display location. (b) Tracking display in automated mode, placed in the peripheral display location.

Tracking performance was assessed by the deviation of the crosshair from the center of the display. This was measured at 1-s intervals and was expressed as a root mean-square (rms) error. The rms error is a traditional overall measure of tracking that many are familiar with in tracking research [37]. The rms error was chosen as the only tracking-performance measure due to its compatibility with parametric statistical tests as well as its near Gaussian distribution, which the square-root transformation of the measure provides.

2) Monitoring Task: Multiple-display monitoring is one of the more important and growing features of complex systems control. There is a sequential increase in the use of these automated and semiautomated control options. Consequently, the monitoring of displays is an increasing component of demand, which imposes considerable load on the operator [2]. The multiple-monitoring tasks in the present assemblage are designed to address these questions. The present monitoring subtask had two components: 1) light displays and 2) gauges shown as graduated-sliding indicators. These are shown at the upper left of the left CRT in Fig. 1 and in the same position on the schematic representation shown in Fig. 2. There were a total of five colored lights. Four are represented in the top-left corner of the display in Fig. 2, while the fifth light is the horizontal bar beneath the four gauges, which are shown beneath the lights. These configurations were created to represent a collection of warning lights and gauges that the pilots encounter in the cockpit in the course of their normal duties. The lights could be in one of two states: either on or off. One component of monitoring involves the recognition of the status of two green lights which are normally on, and one yellow and two red lights which are normally off. If any of these lights change status, the participant had to press the appropriate stimulus-response mapped function key to restore the light to normal status. Four deviations each of the lights and gauges were presented randomly over each 5-min interval. Two such intervals composed each full trial. Response time and accuracy to this task are taken as measures of monitoring performance efficiency. A second monitoring task requires attending to four graduated-sliding indicators or gauges. The indicators vary continuously about the midpoint of the column. The participant is required to monitor the scales for deviations above criterion yellow (first hash mark) and red (second hash mark) levels, which are not shown in detail on Fig. 2 but are evident in Fig. 1. Participants are instructed to interpret deviations above the yellow hash mark as a warning. When the indicator rises above the red hash mark, participants are required to press the appropriate key to reset the indicator. To reduce predictability, the indicator does not always rise to the red hash mark after reaching the yellow hash mark. For this monitoring task, performance was assessed in terms of participants' response times to changes in either the light or gauge status when it had moved out of tolerance. The number of missed signals and false responses were also recorded.

3) Fuel-Management Task: The fuel-management task assesses the operator's ability to monitor and manage a set of simulated fuel tanks using the decision-making strategies (see Figs. 1 and 2). A schematic diagram of a system of interacting tanks and connecting pumps is displayed on the MINSTAR screen. The participant's task is to keep the outer wing tanks (the first and last in the display) at half capacity, i.e., 2500 gallons. This is accomplished by transferring fuel to and from the other three tanks via pumps with differential flow rates. Task complexity can be increased by programming pump failures, which stop the fuel flow in the respective direction. The failures are indicated to the participant by the pump being displayed in red. Fuel levels in each tank are indicated both by a number displayed below each tank and by an analog visual representation of fuel level. Fuel is transferred between tanks by six pumps, which are opened or closed by buttons mounted below the monitor. Fuel is "consumed" from outer wing tanks at the rate of 800 gal/min. The pump from the midline tank to the inner wing and outer wing tanks transfers fuel at the rate of 600 gal/min. Movement from the inner to outer wing tanks occurs at the rate of 800 gal/min. Continual pump activations and deactivations are required to maintain the outer wing tanks at target levels, i.e., 2500. The level of the fuel in the target (outer) fuel tanks was recorded every 5 s. The configuration of the fuel-management task in the automated mode is shown in Fig. 4(a) for the central location and Fig. 4(b) for the peripheral location. Fuel-management error was calculated as the absolute deviation from the goal level of 2500 for each end tank. Error was averaged for the two measured tanks and used as the index of performance.

4) Perceived Workload Assessment: As well as measures of the objective performance from the three subtasks already



(a)

(b)

Fig. 4. (a) Schematic of the fuel-management task when in the automated mode. This version shows the central display location. (b) Schematic of the fuel-management task when in the automated mode. This version shows the peripheral display location.

noted, participants were asked to provide their response on a measure of perceived cognitive workload. There are a number of established techniques for such workload assessment [38]. One of the most thoroughly investigated and validated of these techniques is the subjective workload-assessment technique (SWAT). The details of this procedure have been given previously [39]. SWAT requires participants to first complete a sorting task prior to any performance. This sorting procedure allows them to identify their own individual perception of baseline workload state by comparing the three respective sources *a priori*. These three sources are time load, mental effort, and stress. During performance, at the specified times, participants rate their current state by indicating 1 for low, 2 for medium, or 3 for high on each of the three scales as they are presented in the message window (see Fig. 2). At the designated points of each trial (4:45 and 9:45 of the 10-min trials), the participants provide these numerical values, which are recorded by the experimenter for subsequent analysis.

C. *Experimental Design and Procedure*

Each of the ten pilots performed eight 10-min trials. The between-participant factor was the location of the display when in the automated mode [i.e., central versus peripheral, cf., Fig. 3(a) and (b) and Fig. 4(a) and (b)]. Five pilots were each randomly assigned to these two respective display conditions. In the manual condition, the tracking subtask appeared in the center of its CRT. The two forms of the tracking display, when automated, are shown in its central location [Fig. 3(a)] and its peripheral location [Fig. 3(b)]. The term “peripheral” is used since the automated display was in the periphery of that CRT. The equivalent manipulations of the fuel-management task is illustrated in Fig. 4(a) and (b), respectively. The within-participant factor was automation availability and initiation. Whenever the pilot selected an automation option, the system performed without flaw on that subtask. Pilots were informed that an automated subtask might fail and, thus, could not be forgotten, but failure would be exceptionally rare. These conditions closely resembled actual operational conditions in which automation failure is often very low ($<0.5\%$) as compared to other recent investigations in which the failure of the automated system is abnormally high, sometimes in excess of 20%. Pilots were given no *a priori* instructions about the priority of any task order, although as later results indicate, their previous experience most probably resulted in some degree of personal subtask prioritization.

The order of trials was a balanced rotation across participants. The first participant performed the trials in order 1 through 8, while the next participant performed the trials in order 2 through 8, followed by order 1, and so on. With each trial consisting of monitoring, tracking, and fuel management, the following eight conditions of automation defined the universe of 10-min trials.

1) Manual operation of all tasks (MANUAL). All three subtasks, monitoring, fuel management, and tracking are performed manually.
2) Pilot-Initiated Automation of Tracking (PIAT). The monitoring and fuel-management subtasks are performed manually. The tracking subtask may be automated at the pilot’s discretion via the trigger on the flight stick. The display reduces in size and appears in the location prescribed by the between-participant condition. The pilot may also reacquire manual control of the tracking subtask via a second activation of the trigger on the flight stick.
3) Pilot-Initiated Automation of Fuel Management (PIAF). The monitoring and tracking subtasks are performed manually. The fuel-management subtask may be automated at pilot’s discretion via the response button adjacent to the fuel-management display. The display reduces in size and appears in the location prescribed by the between-participant grouping. The pilot may reacquire manual control of the fuel-management subtask via the same response button used to initiate the automation.
4) Pilot-initiated Automation of Tracking and Fuel Management (PIATF). The monitoring subtask is performed manually. The tracking subtask may be automated at pilot’s discretion via the trigger on the flight stick. The display reduces in size and appears in the location prescribed by the between-subject condition. The pilot may also reacquire manual control of the tracking subtask again via the trigger on the flight stick. The fuel-management subtask

may be automated at pilot's discretion via the response button near the fuel-management display. The display reduces in size and appears in the location prescribed by the between-subject condition. The pilot may reacquire manual control of the fuel-management subtask via the same response button used to initiate the automation.

5) Automated Tracking (AT). The monitoring and fuel-management subtasks are performed manually. The tracking subtask is automated by the system for the duration of the trial. The pilot can do nothing with respect to the tracking subtask except to monitor its performance.
6) Automated Fuel Management (AF). The monitoring and tracking subtasks are performed manually. The fuel-management subtask is automated by the system for the duration of the trial. The pilot can do nothing with respect to the fuel-management subtask except to monitor its performance.
7) Pilot-Initiated Automation of Tracking/Automated Fuel Management (PIAT/AF). The monitoring subtask is performed manually. The tracking subtask may be automated at pilot's discretion via the trigger on the flight stick. The display reduces in size and appears in the location prescribed by the between-subject condition. The pilot may also reacquire manual control of the tracking subtask via the trigger on the flight stick. The fuel-management subtask is automated by the system for the duration of the trial. The pilot can do nothing with respect to the fuel-management subtask except to monitor its performance.
8) Pilot-Initiated Automation of Fuel Management/Automated Tracking (PIAF/AT). The monitoring subtask is performed manually. The fuel-management subtask may be automated at pilot's discretion via the response button near the fuel-management display. The display reduces in size and appears in the location prescribed by the between-subject condition. The pilot may reacquire manual control of the fuel-management subtask via the same response button used to initiate the automation. The tracking subtask is automated by the system for the duration of the trial. The pilot can do nothing with respect to the tracking subtask except to monitor its performance.

Pilots were instructed to initiate automation on the available subtasks only when they felt their overall performance was deteriorating unacceptably due to the collective level of summated demand. Pilots were informed that the failure rate of automation was very low but that they should not forget any automated subtask since failure was still a possibility. This very low frequency of automation failure accorded with their everyday experience, since pure mechanical failure of automation is indeed very low in modern flight systems. Given then that the perceived level of potential failure was very low and the actual failure rate we imposed in this paper was zero, we assume that trust played no prominent role in the present procedure.

In the whole experimental sequence, the monitoring subtask was never automated. Data were obtained for all subtasks that were manually operated in any of the combinatorial condition. No tracking or fuel-management data were collected for PIAT/AF, PIAF/AT, and PIATF conditions. Only the effect of these automation invocations on the monitoring performance was measured. For each individual subtask whose automation was at the pilot's discretion, pilots were encouraged in the instruction set to choose automation whenever they believed that their personal momentary performance was not satisfactory on all three subtasks. In this paper, inferences and conclusions are drawn based upon subtask performance. This is the case, because the interface question requires pairwise comparison of elements, one of which is under some level of automation. At the termination of the experimental sequence, the participant pilots were debriefed with respect to the specifics of the displays and automation invocation methods.

III. EXPERIMENTAL RESULTS

A. *Tracking Performance*

The rms error for tracking was recorded at a sampling rate of 1 Hz during all experimental trials. Mean rms error was calculated for each participant in the MANUAL [mean ± standard error] (66.178 ± 1.398), the PIAF (54 ± 1.148), and the AF (52.045 ± 1.19) conditions. These data were analyzed via repeated measures analysis of variance (ANOVA) procedure, grouped by configuration/location as a between-participant factor. This mixed ANOVA indicated a significant effect for condition ($\mathbf{F}[2,16] = 5.576, \underline{p} < 0.05$). Planned *post hoc* contrasts revealed significant differences between the MANUAL and the AF condition in which the rms error in the MANUAL condition was significantly higher than the rms error in the AF condition. Since the consistency of tracking is also important, as well as its mean deviation, a further ANOVA was performed on the variance of the rms error. Results for the variance of rms error indicated a significant difference for condition ($\mathbf{F}[2,16] = 4.553, \underline{p} < 0.05$), where the scores were MANUAL (1984.484 ± 8.042), PIAF (1576.359 ± 8.333), and AF (1428.856 ± 7.729), respectively. Planned contrasts subsequently revealed a significant difference only between the MANUAL and the AF conditions.

The tracking results confirm, unsurprisingly, that whether the pilot chooses to offload the task or the system automates that task, the tracking performance improves compared to circumstances in which all tasks are performed manually. Pairwise comparison indicates that, for both mean and variability of performance, it is the automated removal of the fuel-management subtask that is the most beneficial. The pilot-initiated procedure was an intermediary stage in which differences could not be established from the other two conditions, i.e., Manual and AF. The small difference between the AF and PIAF conditions is due to the lag with which each pilot chose to initiate the automation in the PIAF condition. Recall that in the AF condition, the fuel-management subtask is automated during the entire course of the trial. It is apparent that pilots chose to use the automation appropriately in order to achieve similar performance to that of AF condition, as evidenced by the absence of performance difference between in the AF and the PIAF conditions here.

The whole of the effect of fuel-management status on tracking behavior lay in the invocation procedure. That is, there were no interface configuration effects and no interactive effects between interface configuration and invocation procedure. These results provide evidence that how automation occurs is apparently of greater effect than where displays are located but, of course, this statement is only true for the performance of the tracking subtask. The overall picture is inevitably much more complex.

B. Fuel-Management Performance

The level of fuel in each of the two "goal" fuel tanks was recorded every 5 s, as well as being recorded subsequent to each fuel-pump activation. The levels for the two goal tanks were averaged and an absolute deviation from the target 2500 gallons was obtained. This score was designated as fuel error. Mean fuel error was calculated for each participant in the MANUAL, PIAT, and AT conditions. Analysis of these data indicated no significant effect for automation invocation procedure on performance. Means were analyzed via repeated measures ANOVA, grouped by the configuration/location between-subject factor, which did indicate a significant effect ($\mathbf{F}[1,8] = 5.269, \underline{p} < 0.05$). These results showed that, collapsed across types of automation conditions, e.g., AT and PIAT, fuel-management error was approximately double when the automated tracking appeared in the central display location (239.087 ± 3.208) compared to the peripheral display location (123.6 ± 2.808). These results indicate that displays, which can easily recapture the attention of pilots, can have a significant degree of performance benefit, but again, this statement is constrained to the fuel-management subtask only.

Consistent performance in high-demand tasks is also desirable and, therefore, performance variances for fuel error in the MANUAL, PIAT, and AT conditions were analyzed. The ANOVA for fuel error indicated a significant condition effect ($\mathbf{F}[2,16] = 4.945, \underline{p} < 0.05$). Planned contrasts revealed a significant difference between PIAT and AT conditions.

The suppression of variability in the MANUAL and PIAT conditions seems to indicate that sampling, resampling, and attention capture are also important in this context. The fixed allocation in the AT condition means that participants apparently neglected the tracking task, despite the possibility of automation failure of which they are informed. This neglect of the automated tracking task may be due to the pilots being "too far out of the loop" of this control task. The exchange of control itself seems beneficial in suppressing variability and focusing the pilots' efforts on the strategies necessary for the fuel-management subtask. What is clear is that the professional pilots treated tracking and fuel-management subtasks very differently—the location effect occurs only when tracking is the automated subtask. This is important since it implies a clear strategic approach by pilots that gives primacy to tracking. In other words, when tracking is in the MANUAL or PIAT mode, there is not as much variability in fuel management since the pilots are still "focusing" on the tracking subtask. Second, despite surface appearances, each task is one of continuous control and it may be the bandwidth of what is perceived of as acceptable performance that differs. What is also clear is that there are tradeoffs between subtasks and potentially micro tradeoffs even within any single performance trial. Eventually, appropriate interface design for multiple subtasks will have to reflect such tradeoffs intrinsic to multiple-task performance.

TABLE I
MONITORING LIGHTS MISSED

Condition	Mean	(S.E.)
AT	3.6	(0.44)
PIATF	3.1	(0.55)
PIAT	2.9	(0.58)
Manual	2.4	(0.40)
PIAF/AT	2.2	(0.43)
PIAF	2.0	(0.34)
AF	1.4	(0.35)
PIAT/AF	1.3	(0.35)

C. Monitoring Task Performance

Mean response times for monitoring lights and gauges were calculated for each participant for all conditions. These response times were analyzed via repeated measures ANOVA, grouped by the configuration/location between subject factor. No main or interactive effect proved significant for either light or gauge monitoring response time. However, for misses on the light monitoring task, the ANOVA revealed a significant effect for both invocation procedure [$\mathbf{F}[7,49] = 2.436$, $\underline{p} < 0.05$ (see Table I)] as well as display location ($\mathbf{F}[1,7] = 10.563, \underline{p} < 0.05$). The latter effect showed that a significantly greater number of monitoring lights were missed with the peripheral (3.308 ± 0.397) compared with the central (1.425 ± 0.272) location. There were no comparable significant effects for the misses on gauge monitoring. The overall results for monitoring showed that pilots performed reasonable well in the manual condition compared to all other combinatorial conditions (cf., Table I; values shown are for each 5-min interval, two such intervals per trial, see also measures of workload; the total number of signals per 5-min period was four). This may be due to context specific practice in that pilots are frequently called upon in contemporary cockpits to respond to presented warnings. Therefore, it is possible the light color changes may have been more salient to the pilots than the gauge deviations. These overall monitoring results are unlikely to be due to a vigilance decrement, since the temporal conditions for such a decrease are not present [40].

D. Perceived Workload Response

Data for the subjective measures of cognitive workload, coded as time load, stress level, and mental effort, were collected at 4:45 (midpoint) and 9:45 min (endpoint) of each 10-min experimental trial. Participants responded to the question "What is your time load?" with 1 (much spare time), 2 (some spare time), or 3 (no spare time). A mean response value was obtained for each condition using data collected at

TABLE II
SWAT TIME LOAD

Condition	Mid		End	
	Means	(S.E.)	Means	(S.E.)
Manual	2.3	(0.22)	2.7	(0.22)
PIAT	1.8	(0.25)	2.0	(0.22)
AT	1.7	(0.26)	2.0	(0.26)
PIATF	1.6	(0.26)	1.9	(0.27)
PIAF	1.5	(0.27)	2.0	(0.26)
AF	1.5	(0.27)	1.7	(0.26)
PIAF/AT	1.5	(0.23)	1.6	(0.26)
PIAT/AF	1.1	(0.18)	1.4	(0.26)

TABLE III
SWAT STRESS LEVEL

Condition	Mid		End	
	Mean	(S.E.)	Mean	(S.E.)
Manual	1.8	(0.25)	2.3	(0.22)
AT	1.4	(0.23)	1.6	(0.26)
PIAT	1.3	(0.22)	1.5	(0.23)
PIATF	1.2	(0.21)	1.8	(0.21)
PIAF	1.2	(0.21)	1.4	(0.23)
AF	1.1	(0.18)	1.6	(0.23)
PIAF/AT	1.1	(0.18)	1.2	(0.21)
PIAT/AF	1.0	(0.00)	1.0	(0.00)

TABLE IV
SWAT MENTAL EFFORT

Condition	Mid		End	
	Mean	(S.E.)	Mean	(S.E.)
Manual	2.1	(0.27)	2.5	(0.23)
PIAT	1.7	(0.22)	1.8	(0.21)
PIAF	1.5	(0.23)	2.0	(0.22)
PIATF	1.4	(0.23)	1.9	(0.27)
AF	1.4	(0.23)	1.6	(0.23)
PIAF/AT	1.4	(0.23)	1.6	(0.23)
AT	1.2	(0.21)	1.6	(0.23)
PIAT/AF	1.0	(0.00)	1.1	(0.23)

the mid and endpoint of each trial. The data for the midpoint scores were then analyzed via a repeated measures ANOVA, blocked by the configuration-location between-subject factor. Analysis revealed a significant effect for invocation condition $(\mathbf{F}[7, 56] = 5.549, \underline{p} < 0.001)$. Planned comparisons revealed that time load at the midpoint was perceived as significantly higher in the MANUAL condition versus all other conditions, except AT and PIAT (see Table II).

A similar analysis was employed for time-load responses obtained at the endpoint of the trial. In this subsequent analysis, a significant main effect for condition was again evident $(\mathbf{F}[7, 56] = 5.444, \underline{p} < 0.001)$, which at this juncture showed that the MANUAL condition was significantly different from all other conditions by trial's end.

These results, in demonstrating that perceived time load was greatest in the MANUAL condition, indicates that this facet of perceived workload was sensitive only to the difference between performance of all subtasks versus all other conditions. It is also interesting that discretionary control over subtasks appears to impose greater temporal workload than adaptive partitioning of those subtasks (cf., Table II). Most probably, the reason that time load did not go toward "one," i.e., much spare time in the latter conditions, was the continued monitoring demand that did not change.

Participant responses to the question "What is your stress level?" were also scored 1 (very little stress), 2 (moderate amount of stress), or 3 (extensive amount of stress). A mean response value was then obtained for each condition using responses recorded at the midpoint and endpoint of the trial. These data were also analyzed using a repeated measures ANOVA, blocked by the configuration-location between-subject factor. This analysis revealed a significant condition effect $(\mathbf{F}[7, 56] = 3.769, \underline{p} < 0.01)$. Planned comparisons revealed the MANUAL condition to be significantly different from all other conditions, except PIATF and AT (see Table III).

A similar analysis was then conducted for responses obtained at the trial endpoint. A main effect for condition was confirmed $(\mathrm{F}[7, 56] = 6.424, \underline{p} < 0.001)$. As with the time load, planned contrasts revealed a significantly higher perception of stress in the MANUAL condition when compared to all other conditions. However, in the present case, the PIAT/AF showed significantly lower stress scores than all other conditions except PIAF/AT condition (see Table III).

Participant responses to the question "What is your mental effort?" were scored 1 (very little), 2 (moderate amount), or 3 (extensive amount). A mean value was obtained for each condition using responses for the midpoint collection. Data were analyzed via a repeated measure ANOVA, blocked again by the configuration-location between-subject factor. Analysis revealed an effect for condition $(\mathbf{F}[7, 56] = 4.975, \underline{p} < 0.001)$. Planned comparisons revealed that the MANUAL condition was significantly different from all other conditions except PIAT and PIAF. Generally, conditions involving adaptive automation had a lower perception of mental effort (see Table IV). Data for the mental-effort question collected at the endpoint were analyzed in a similar fashion. Analysis revealed the now expected significant effect for condition $(\mathbf{F}[7, 56] = 5.694, \underline{p} < 0.001)$. Planned contrasts indicated that the MANUAL and PIAT/AF conditions were significantly different from all others (see Table IV), in which again, the MANUAL condition proved the most loading while the PIAT/AF proved the least taxing. Overall workload obviously reflected these trends for individual subscales with the MANUAL condition clearly identified as the most taxing overall, together with a clear pattern of the pilot-initiated automation conditions imposing the least perceived workload, although the latter pattern is somewhat less evident than the MANUAL effect.

IV. DISCUSSION

That the automation of any one subtask has an effect on overall, multiple-task performance is self-evident. However, exactly which one of a suite of subtasks is automated, how that automation occurs, and the subsequent display of information following automation exerts much more subtle effects. The preferred way of documenting these effects would be to have some overall assessment of how well the operator is performing under the respective conditions of subtask automation. However, despite a number of efforts, there is no agreement over what this summed metric or “figures of merit” should be composed of. Thus, conclusions from this paper were drawn based upon summated individual subtask performance. However, one clear research goal for future work on human interaction with automated systems must be some agreed form of overall competence measure, which synthesizes both objective and subjective sources of information.

A. *Display Dynamics*

The present results revealed a difference in performance strategies as used by pilots versus flight-naive participants [20]. It was confirmed that the strategies of professional pilots did differ when tracking was automated compared to when fuel management was automated, a difference which was not present in flight-naive participants. When tracking was automated, the pilots’ fuel error was affected by the location change of the tracking display, while the fuel error of the nonpilots who performed the same series of trials in a previous study was not affected by the location change [20]. For pilots, when the tracking display was placed in the peripheral location, it fostered better performance than in the central location. This advantage may well have to do with attentional dynamics and the suppression of distraction effects, although the precise nature of this benefit has still to be fully articulated.

Demand-contingent attention strategies are necessary in real life multitasking situations, such as is evident in the modern cockpit because of the stochastic nature of the informational environment. A pilot must not only sample or scan a display frequently in order to maintain a knowledge of the system’s activities, but the pilot must sample or scan that display at the appropriate time. In other words, the pilot’s sample rate of a display must be in close agreement with the statistical event rate of that display [41]. The pilot does not want to sample a dynamic display in a manner that is out-of-phase with that display’s information gradient. For this paper, it is evident that the change in display location forced the pilots to change their attention strategies. This forced change in attention may be necessary in order to adjust when attention is paid, since the automation of one subtask out of several subtasks will change the statistical structure of the optimal sampling times for each display. This is particularly true, if the subtask that is automated is one that does not require constant attention when it is performed manually, e.g., the fuel-management task. If a constant attention subtask such as the tracking is automated, the pilot is free to pay more attention to the remaining subtasks. In this paper, this appears to be the reason for the increased variance in the fuel error once the tracking task was automated. It is critical to note that these strategies mean that interface configuration has a strong influence on pilot behavior. This argues strongly for continued investigation of interface structure as an important determinant of pilot capability in the adaptive-automation realm.

B. *Intrinsic Feedback*

The change in the size of the display for the automated subtasks, as well as its location change in the one condition, are observable forms of feedback. The operator is aware that control of that task has been given to the system. However, the effectiveness of the feedback depends on the effort needed to convert this information into a coherent interpretation in the context of the subtask and its place within the multiple tasks being performed [15]. It appears that this form of intrinsic feedback was effective in that the offloading of one of the subtasks, whether it was tracking or fuel management, improved the performance of the other subtasks. Thus, pilots understood that automation was in control of the respective subtask and, therefore, they were available to focus more of their efforts on the remaining subtasks. In further work, it will be necessary to partition such intrinsic feedback effects from the independent configuration effects themselves. However, from the present results, it is evident that these changes were potent cues and useful to the pilot participants

C. *Perceived Workload*

The overall data for perceived workload are very consistent. Both the individual scales and collective summed workload show that the manual condition is perceived consistently as that of the greatest demand. However, it should be remembered that on some of the subscales, at either the mid or endpoint, this difference between manual and partially automated conditions does not always reach a statistically reliable one. Conditions in which a single subtask is offloaded in some fashion are perceived as the next highest load, and the lowest load is perceived in combinatorial conditions in which multiple subtasks are offloaded. Residual workload is that which is experienced from the monitoring subtask alone. Mere control, i.e., the PIATF condition, did not reduce workload to its lowest level, neither did it significantly reduce the stress component of workload as some theorists have argued [42]. This is of interest since the enforced monitoring of display is itself clearly stressful [2], [43], while the act of switching between manual and automatic modes could itself be considered a source of workload. The conclusion here is that workload is a useful reflection of the gross level of overall multiple task activity, and where workload is a trigger for adaptive allocation, the amount of demand may be critical compared to the composition of that demand. Looking generally at the perceived workload results, it is evident that workload was at its minimum for all scales (time load, stress, and mental effort) when the tracking subtask task was automated under pilot control and the fuel-management subtask was automated by the system. Again, such trend was not ubiquitously evident in a full statistical sense.

Although fuel-management-performance variability was suppressed while tracking automation was under the control of the pilot, it was significantly greater when the control of automation for tracking was given to the system. It is interesting then when looking at the perceived workload results for the AT and PIAT conditions that they are not fundamentally different from each other. It appears that the pilots may have become under loaded in the AT case and, therefore, spent their attentional capacity adjusting their fuel-management strategies which, potentially, contributed toward the elevated variance in fuel-management performance.

D. Pilot Preferences

A participant debrief was administered to the pilots following the experiment, which elicited information regarding preferences for automated display location and configuration as well as comments on the use of automation itself and its effect on their workload. Nine out of the ten pilots agreed that the tracking automation decreased their workload. Informal comments included observations that the workload decreased dramatically and that the tracking automation also decreased the attention requirement. Eight of the ten pilots agreed that the fuel automation also decreased the workload (one exception here was due to the absence of a response for this question). With respect to automation of the fuel-management subtask, comments included the fact that they could then focus on other tasks; it was not as helpful as the automated tracking and, conversely, that it was more helpful and realistic with the fuel subtask automated. Seven of the pilots would have preferred changing both size and location of the displays if it is required for automation, but two pilots preferred just a size change for the automation display. When choosing the location of the automated display, there was more of a discrepancy in preference. Four pilots indicated that they would have preferred an edge (peripheral) display, two pilots preferred the center display, and the others expressed no particular preference. It is also interesting to note that the pilots commented that the gauges (part of the monitoring subtask) were highly predictable and this might explain the fast response times for the monitoring subtask and the absence of misses for the gauges themselves.

V. SUMMARY AND CONCLUSION

The present results imply that there are bandwidths of acceptable performance on each subtask and that pilots have priorities related to each of these levels. Given that, indeed, there are such differing performance strategies [44], it is posited that the pilots' present performance is related to visuo/attentional scan pattern, which is, of course, influenced by the interface configuration. The question of how to promote performance under differential automation status is one that is informed by this observation. This paper confirms the importance of configuration changes for pilots during adaptive automation. The evidence indicates that it is the strategy changes driven by perceived priority and interface structure that directly mediate pilot-performance capacity. The pilots' evident and continued emphasis on the primacy of the tracking subtask drives the present results and accounts for their differences with a previous flight-naïve sample performing the same task [20]. The next logical step is to use eye tracking in order to distinguish exactly how pilots' performance is related to their scan patterns as the displays change under variation in automation status. It would also be beneficial to test for these effects using a flight simulator with standard instrumentation and flight tasks. In particular, further investigation may include adaptive automation of nonprimary tasks to determine, if the pilots are controlling their attention allocation efficiently.

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