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Performance, Workload, and Fatigue Changes Associated With Automation

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The experiments discussed in this article addressed the influence of part-task automation on operator performance, workload, and fatigue in a multitask environment. The overall task environment included tracking, resource management, and multiple monitoring subtasks. Slower, more accurate monitoring and better resource management were observed when the tracking subtask was automated. Although lower workload was reported when tracking was automated, fatigue increased equally during periods of manual and automatic tracking. When participants could control workload by shifting between manual and automatic tracking, participants with 7 hr of training switched between automatic and manual tracking. Their performance during optional automation periods was superior to their performance in conditions in which only manual control or only automated control was available. The findings argue for the utility of discretionary control of automated systems.

Our technological society has committed itself to a course of development in which automation and semiautomation promise to provide an eventual resolution to many problems of complex system control (Zuboff, 1988). Although the role of the operator is considered trivial by some and critical by others (Billings, 1991), the fundamental nature and characteristics of this interaction between human operators and automated systems is still a matter of debate and design evolution (Hancock, 1993; Weiner, 1988). Nowhere is the problem concerning the division of control between operator and machine more obvious than in contemporary flight systems. Aircraft, like all complex systems, must exist between static and chaotic states in order to adapt to the demands of unpredictable events while taking advantage of

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environmental regularities. With respect to this balancing act, the human operator remains the critical component for providing adaptive response (Hancock & Chignell, 1987; Rouse, 1985). However, the way in which the human role is sculpted with respect to the introduction of automation is a critical question. We cannot exhaustively test all evolving technical systems, therefore, the development of principles and guidelines derived from experimental manipulations is an important design need. A critical contemporary concern is the assessment of the energetic state of the human operator and how such information can be used to shape designs for human-centered automation and adaptive task allocation.

In this study we examined performance, fatigue, and workload in a multitask environment in which one subtask (tracking) could be automated or left under operator control. Resource theory (Navon & Gopher, 1979; Wickens, 1980; Wickens, 1984) explains subtask performance in multitask environments using the assumption that tasks compete for limited mental resources. Automation can, presumably, be used to decrease mental demands in situations in which workload exceeds mental resources; thus, automating one task would be expected to improve the performance of nonautomated tasks (Wickens, 1992). A second potential benefit of automation is a reduction in the fatigue that occurs during performance of cognitive tasks (Galinsky, Rosa, Warm, & Dember, 1993). Potentially hazardous performance decrements are associated with pilot fatigue (Lyman & Orlady, 1981); a reduction of mental demands during automation is expected to decrease fatigue and improve system safety.

In operational settings, taskload is dynamic. Typically, task demands threaten to exceed mental resources for short periods; ideally, the level of automation would be increased or reduced as a function of workload to produce maximum system performance (Wickens, 1992). Unfortunately, present circumstances seem directly in contrast with this aspiration and, as Weiner (1988) has noted, automation serves to decrease workload when task demands are low and increase workload when task demands are high. With respect to balancing the fluctuation in task demands, Hancock, Chignell, and Loewenthal (1985) proposed a knowledge-based allocation system to regulate and distribute task components between operator and system based on intrinsic abilities and current capacity as reflected in humans by mental workload level (see also Hancock & Chignell, 1987). However, automation effectiveness is apparently improved when pilots determine the role of automation in system control (Rouse, 1988). Approaches to pilot controlled automation, particularly in fighter aircraft operation, include the Pilot's Associate system in which the pilot determines the role of automation before a mission (Rouse, Geddes & Hammer, 1990). A second approach is an interaction between the pilot and the computer during the mission to distribute task load (Gluckman, Morrison, & Deaton, 1991). Each of these strategies rely upon detailed experimental information about pilot response under differing automation conditions that has yet to be produced. Therefore, this series of studies assessed the effects of automating one task (tracking) in a multitask battery on performance, workload, and fatigue level. Additionally, we compared performance when participants could switch between automatic and manual tracking against responses during periods when only automation or only manual control was available.

METHOD

Because the method for each of the experiments was common across procedures, the following represents a general description. Exceptions to the general method are noted where appropriate.

Experimental Participants

Participants in the two experiments and the pilot study were students, staff, and faculty of the University of Minnesota. The sample consisted of 20 men and 6 women ranging from 21 to 54 years of age with an average age of 27.4. Participants were unpaid volunteers who had no previous experience with the Multi-Attribute Task Battery (MATB; Comstock & Arnegard, 1990).

Performance Assessment

The performance assessment instrument used was the Multi-Attribute Task Battery (Comstock & Arnegard, 1990). MATB is a multitask, generic representation of a complex system. It has been used previously in connection with automation complacency by Parasuraman, Molloy, & Singh (1993) and is described in that work. Because we have made a number of changes to the task, specific presentation details will be described. MATB requires participants to simultaneously perform perceptual–motor (tracking), cognitive,–strategic (fuel management), and perceptual–cognitive (monitoring) tasks, which represent three flight relevant task domains (Parasuraman, Bahri, & Molloy, 1992). Because the MATB represents a generic system, the results observed and the principles developed address systems beyond aviation. The MATB screen is presented in Figure 1.

Monitoring task. The monitoring tasks consisted of striking a key when the green light in the upper left corner was extinguished, striking a second key when the light to the right of the green light turned red, and striking keys that corresponded to gauges in the monitoring panel when the gauge indicators moved beyond one hash mark from the center. The program

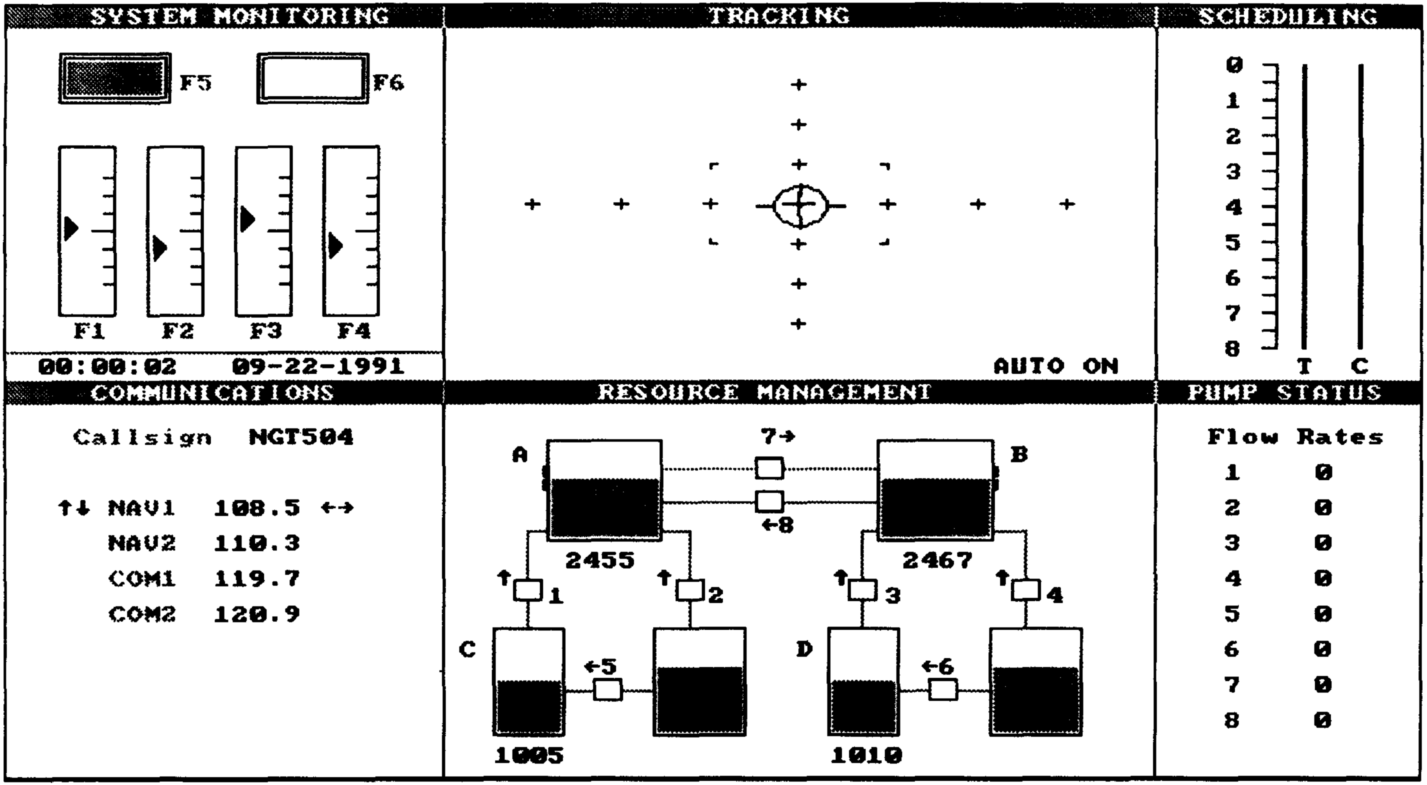

FIGURE 1 MATB screen. The monitoring display is in the upper left corner, the tracking display is located in the upper center of the screen, and the resource management display is in the lower center of the screen.

protocol automatically returned lights to their normal state after 20 sec and gauges were reset after 15 sec out of tolerance.

Resource management task. The resource management task, illustrated in the lower center portion of Figure 1, required participants to activate or inactivate pumps (shown as small squares) connecting the tanks (represented by rectangles). Participants were instructed to maintain the levels in tanks A and B as close to 2,500 gal as possible. The rates of flow from tanks A and B are larger than pumps 2 and 4 can provide, therefore, participants must develop a strategy that involves the periodic use of tanks C and D. Task difficulty can be increased by introducing pump failures that are indicated when the squares representing pumps turn red. In such conditions, no fuel is transferred and alternative pump activation combinations have to be sought.

Tracking task. In the tracking task shown in the upper center of Figure 1 participants used a mouse to maintain the circle within a box in the center of the screen. The speed of circle response to mouse movement is determined by tracking gain. Circle movement speed was calculated by dividing the difference between the deviation of the movement from center by the gain. The tracking gain was set at 45 during all experiments (see Comstock & Arnegard, 1990). General task load was increased by manipulating indicator light changes, gauge deviations, and pump failures.

Subjective Workload and Fatigue Assessment

The NASA-Task Load Index (NASA-TLX; Hart & Staveland, 1988) was used to assess subjective workload. The NASA-TLX includes mental demand, temporal demand, physical demand, performance, effort, and frustration subscales. An overall workload level (OWL) is derived by using a two-step procedure. First, participants perform a pairwise comparison of each of the aforementioned sources of workload. The number of times a particular scale is chosen in comparison with others represents its weighting. There are 15 comparisons; hence weightings total 15. One scale is rated the highest with a score of 5, one is rated the lowest with a score of 0, and the intermediary scales are rated accordingly. All other scales lie ordinally between these extremes. The participant then scores any individual event or trial on a 0 to 100 gradation for each scale. Overall TLX workload is calculated by multiplying these later raw ratings by each respective weighting and dividing the total by 15 to find the number of accumulated weights. (See Hart & Staveland, 1988 for further details.) The Profile of Mood States (POMS; McNair, Lorr, & Droppleman, 1971) was used to assess subjective fatigue. POMS subscales include tension, depression, anger, vigor, fatigue, and confusion. Fatigue changes were assessed by changes in Total Energy, a score calculated by subtracting the POMS fatigue subscale score from the vigor subscale score (Total Energy = Vigor – Fatigue).

EXPERIMENT 1

Experimental Aims and Procedures

Experiment 1 compared the performance, perceived workload, and fatigue of 7 participants manually controlling the monitoring, resource management, and tracking subtasks of the MATB with 7 other participants performing only the monitoring and resource management subtasks. The tracking display was present for the second group, but the target was maintained in the central portion of the screen without subject action. Experiment 1 was designed to evaluate the effects of offloading one of the three MATB subtasks to automation. Participants were randomly assigned to one of two groups. The first (Manual) group was asked to perform all three subtasks—tracking, resource management, and monitoring—under manual control throughout the performance period. The second (Automation) group was asked to perform the resource management and monitoring tasks under manual control while the tracking subtask was controlled by the system under automation. Participants in the latter group still assessed tracking status because automating a task is not equivalent to forgetting a task. Parasuraman and his colleagues noted that reducing a continuous control task to an automated one is the equivalent of transferring the task characteristics from momentary control to sustained attention (Parasuraman et al., 1993).

After receiving detailed instructions regarding the function of each MATB subtask, participants were provided a practice session in which they familiarized themselves with each subtask, one task at a time. Immediately after completion of the practice session, participants completed the POMS, then began the 30 min MATB session. The configuration of the MATB interface depended upon the assignment of a participant to the manual or to the automatic group. Each session was composed of six 5-min blocks separated by completion of a NASA-TLX measure. Following the session, each participant completed the POMS a second time and indicated the relative contribution of each of the six NASA-TLX factors to overall workload (the NASA-TLX weighting procedure). Task loads between 5-min blocks were varied by changing the frequency of lights or gauges that required resetting and the frequency of pump failures. The number of display changes for the 5-min Blocks 1 through 6 were 22, 21, 20, 30, 31, 22 changes respectively. Display changes and their time of occurrence were identical.

RESULTS

Performance Responses

Repeated measures analysis of variance (ANOVA) indicated that the performance of the manual tracking participants differed significantly on all elements of the monitoring task: green light $F(1, 306) = 4.05$, $p < .045$; red light $F(1, 1155) = 3.67$, $p < .001$; and gauges $F(1, 692) = 9.34$, $p < .002$. Manual tracking participants had shorter response times (RTs) to each of the three monitoring tasks. Responses when the appropriate light change or gauge deviation was not present (false alarms) were significantly more frequent for manual tracking participants, $F(1, 1155) = 36.11$, $p < .001$. There was also a trend toward fewer frequently missed signals during manual tracking.

Comparison of response latencies to the three monitoring tasks indicated that participants in both groups responded very rapidly when extinguishing the red light. Their response latencies to reactivate the green light were, in comparison, significantly longer. The longest response latencies were for detection and correction of out-of-range gauge deviation. False alarms were most frequent for gauges, and participants least often incorrectly indicated that the red light was on. The false alarm frequency of automatic and manual tracking participants did not differ during the first three blocks, but manual tracking participant false alarm frequency increased during the second half of the session.

Quality of resource management accuracy of manual and automatic tracking participants differed significantly, $F(1, 4043) = 505.90$, $p < .001$. Increased resource management error during manual tracking was associated with fewer pump activations and deactivations. The frequency of pump activations and deactivations decreased in both groups during the fourth session in which task load increased in the manual and automatic tracking groups.

Multivariate analysis of variance (MANOVA) indicated that performance (response times to the red and green lights and to the gauges, and the resource management error) during Blocks 1 and 6 improved significantly as a function of time on task, $F(4, 9) = 5.21$, $p < .019$. (See Table 1.) Blocks 1 through 6 were matched exactly in terms of all task demands. Such improvements are indicative of a learning effect in this complex multitask test. Response time and resource management error results are illustrated in Figures 2 and 3.

Mental Workload Response

Participants in the manual tracking group reported higher workload than participants in the automatic tracking group on five of the six NASA-TLX

TABLE 1
Monitoring Response Time (In Seconds) and Resource Management Error (In Gallons) Versus Time on Task

Task	Time on Task					
	5	*10*	*15*	*20*	*25*	*30*
Red light response time**						
Manual	1.72	1.81	2.3	1.52	1.37	1.39
Automatic	2.29	2.46	2.33	2.06	2.41	1.53
Green light response time*						
Manual	6.01	5.30	6.43	4.34	4.68	2.99
Automatic	6.54	6.45	6.04	4.93	6.58	5.31
Gauge response time**						
Manual	11.59	9.20	8.22	8.02	8.13	6.40
Automatic	11.92	10.26	12.00	9.61	8.18	10.31
Resource management error**						
Manual	508	467	343	690	410	493
Automatic	440	267	196	409	252	242

*$p < .05$. **$p < .01$.

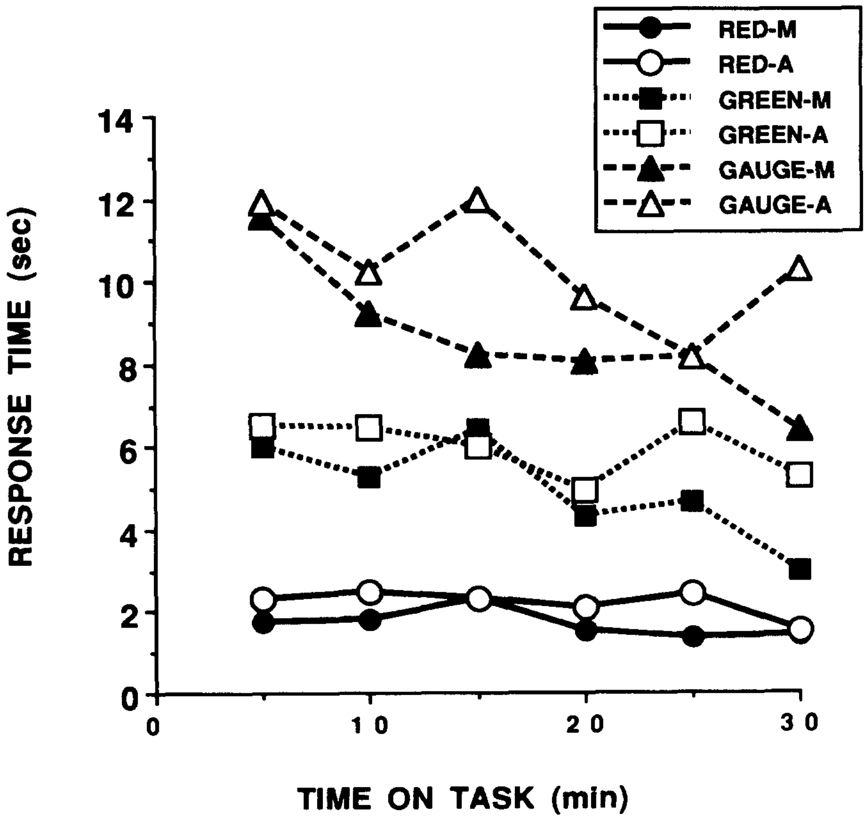

FIGURE 2 Response times for monitoring signals for automatic or manual mode against the time on task.

scales. Differences include significantly higher levels of mental demand, temporal demand, effort ($p < .01$), frustration, and physical demand, ($p < .05$). As a result, OWL was significantly higher for the manual group than for the automatic tracking group, $F(1, 72) = 17.51$, $p < .0001$ (see Figure 4). The performance subscale ratings did not vary between the manual and automatic tracking groups. However, it is important to remember that the manual versus automatic comparison is a between-group comparison. Each of the other NASA-TLX subscales queries the individual about their absolute perception of workload. However, the performance subscale asks participants to compare their own performance against their self-imposed goals. Thus, it is quite feasible that whatever the level of actual performance, participants experiencing different conditions may each be equally happy with their own response. Furthermore, workload levels did not interact with blocks of performance, indicating a relatively stable perceived load over the session.

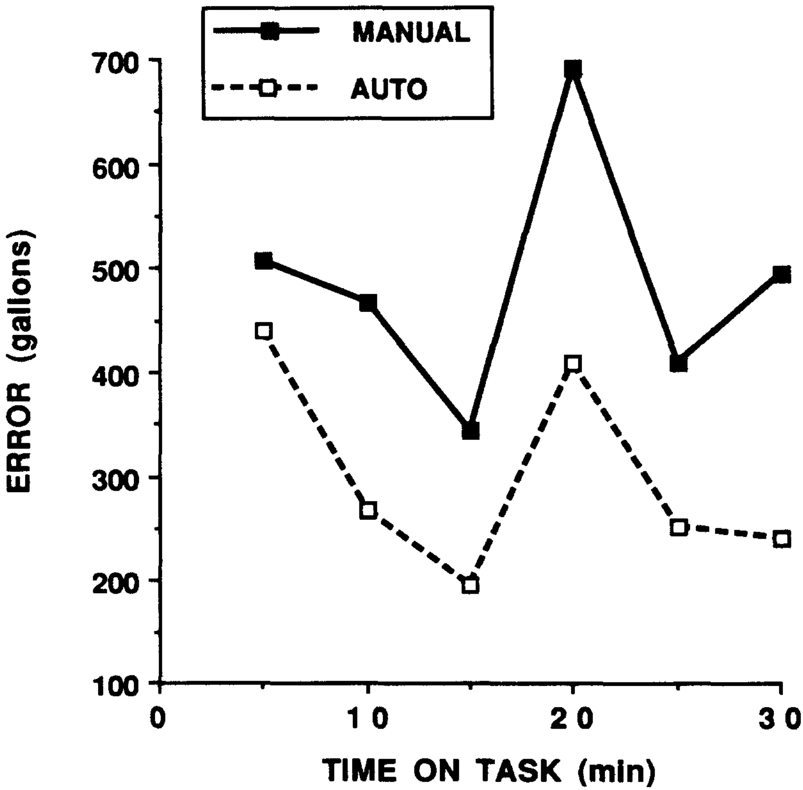

FIGURE 3 Time-based comparison of error values on the resource management subtask divided into automatic versus manual mode.

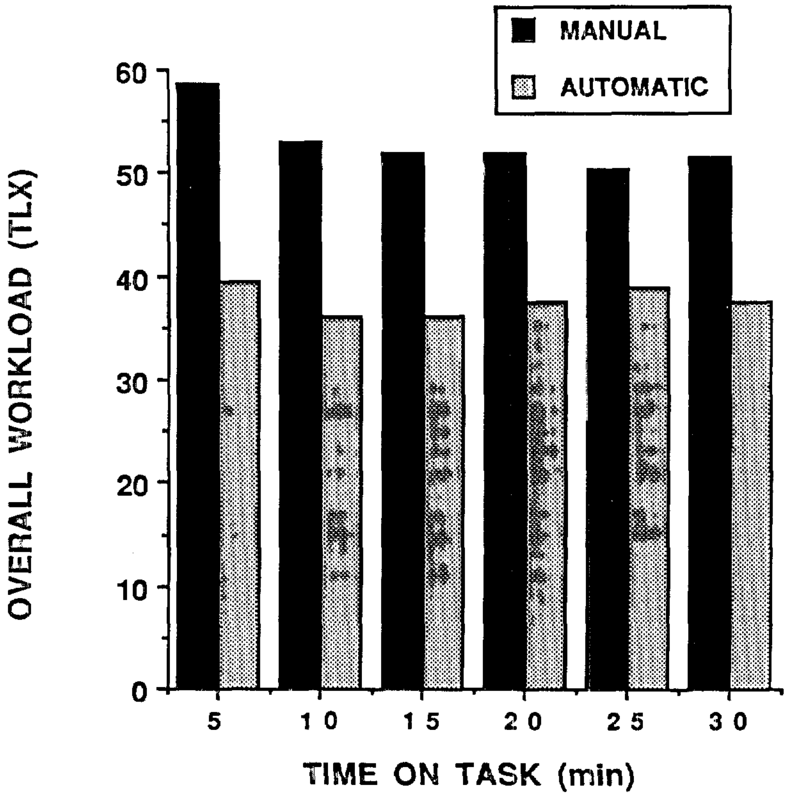

FIGURE 4 Subjective mental workload response versus time on task.

Fatigue Response

A combination of the vigor and fatigue scales of the POMS (Total Energy = Vigor – Fatigue) was used to assess participant fatigue. Participants reported higher vigor and lower fatigue levels than average college students before the session, but participants in both groups reported decreased perceived Total Energy after the session, $t(13) = -2.11$, $p < .027$. The fatigue increase of the automated tracking group was not significantly different from that exhibited by the manual tracking group.

EXPERIMENT 2

Pilot Investigation

Manual tracking participants exhibited little difficulty performing all MATB tasks during low task load periods. However, increased resource management error and faster but less accurate monitoring during the session suggest that participant resources were exceeded during periods of high taskload. We conducted a pilot experiment to find whether participants could dynamically adjust workload by automating tracking during periods of high taskload and resume manual tracking when all tasks could be performed simultaneously.

The procedure was identical to that in Experiment 1 except that participants could alternate between manual and automatic tracking at any time during the session by simultaneously striking the control and F7 keys (a task requiring the use of both hands). Seven individuals participated in this procedure and each was instructed to perform all tasks, but were told that tracking could be automated to decrease workload.

Three of the 7 participants did adjust taskload by automating tracking during high taskload periods and returning to manual tracking when taskload was low. However, 4 participants did not switch between automatic and manual tracking in response to taskload variation. Three participants initially chose the manual condition and never activated the automated tracking option, whereas 1 participant remained in automation mode throughout the session. Participant debriefs determined that the failure of more than half of the participants to adjust workload by switching between manual tracking and automation was the result of the cumbersome procedure required to accomplish the changeover. Further, some participants indicated that they had considered simultaneously performing the entire battery to be a challenge and had been less concerned with errors. Others indicated that they had attempted to minimize the effort required to perform the task and that manually tracking or continually switching between manual control and automation was difficult, therefore, they used automation continuously. Based on these observations, the automation switching procedure was changed and more specific directions were incorporated into the experiment.

Experimental Aims and Procedures

In the first experiment, resource management error was lower and monitoring responses were more accurate but slower during automated tracking than during sessions when tracking was manually controlled. Experiment 2 used 5 participants in a within-subject design, each of whom had 7 hr of experience with the MATB in another experiment and had reached a stable performance level. The simplified, one keystroke procedure for shifting between automation and manual tracking was provided, and pre-session directions explicitly indicated that the best performance included accurate monitoring, resource management, and tracking. Participants completed manual and automatic sessions and a third session, optional tracking. Each session lasted 30 min.

Results

In the optional-tracking session, which allowed switching from manual to automatic tracking, 4 of the 5 participants used the opportunity to adjust task load through automation usage. The 5th participant maintained manual tracking for the entire session. The average manual tracking time per 5-min block was 3 min, 50 sec. Comparison of monitoring performance indicted that participants in this experiment exhibited shorter RTs to the lights and gauges. However, RTs during manual, automatic, and optional-tracking sessions did not differ significantly. A trend toward more frequent false alarms during manual and optional tracking sessions was noted. RTs were stable across the sessions with the exception of a decrease in the red light RT from Trial 1 to Trial 6. As illustrated in Figure 5, resource management during the optional-tracking session was superior to performance in either the manual or automatic conditions, $F(2, 5368) = 36.113$, $p < .001$.

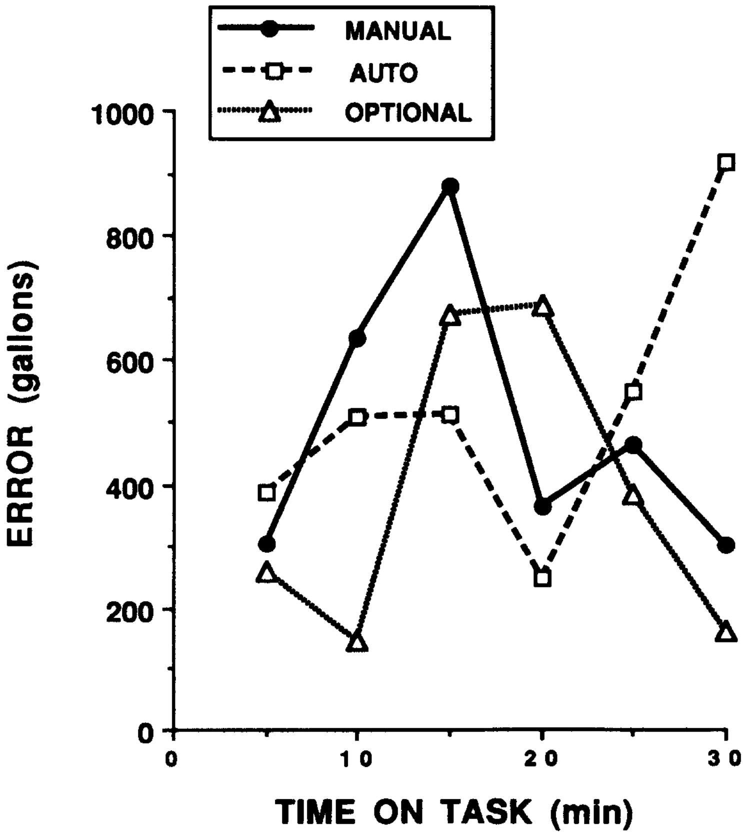

FIGURE 5 Resource management error versus time on task for automatic, manual, and optional tracking modes.

GENERAL DISCUSSION

It is feasible to automate a wide variety of piloting tasks, but the decision to incorporate automation should be determined by the impact on overall system performance, not on the availability of convenient technologies. In this series of experiments, workload and performance were compared during periods of manual and automatic tracking. Furthermore, performance was examined during a period in which participants could switch between manual and automatic tracking. Automating one task in a multitask battery reduced perceived mental demands on the operator, but performance changes in the remaining tasks could not be unequivocally labeled as improved. Changes were complex and related to the interaction of the tasks the operator performed during the two conditions. Monitoring, resource management, and tracking each specific performance requirements that determine the method the operator time-shares these activities. Automating tracking not only decreases task load, it changes quantitative and qualitative ways that the subtasks are shared. When tracking was automated, resource management was more efficient and fewer monitoring errors occurred, but light and gauge response times were longer. With respect to workload, the automatic tracking group reported lower workload compared to the manual group, but fatigue increased equally in both groups.

The decreased task demand produced by automating one task in a high-task-load multitask environment would be expected to improve the performance of remaining nonautomated tasks (Wickens, 1984). More efficient resource management was not observed by Arnegard and Comstock (1991) during automatic tracking sessions; however, their tracking task was less demanding than tracking in these experiments, and the mental demands they imposed may have been insufficient to exceed participant's resources. The more efficient resource management observed during automated tracking in our first experiment is consistent with resource theory. Increased pump activations and deactivations suggest that participants increased the time spent on resource management. The shorter RTs on the monitoring tasks during manual tracking sessions do not appear to be consistent with resource theory, but increased error rate during manual tracking sessions suggests that participants changed their strategy during manual tracking and responded quickly, but more inaccurately, to variations in gauges. Gluckman, Morrison, and Deaton (1991) noted similar collateral performance improvements during difficult tracking sessions that were interpreted to be the result of a strategy change that decreased resources allocated to tracking. They hypothesized that participants shifted from attempting to precisely follow the target during easy tracking sessions to the less demanding positional tracking during difficult tasks. The more rapid monitoring responses during manual tracking sessions are also consistent with a change in the attention produced by the presence of tracking. Continuous tracking requires sustained attention that is mentally demanding (Hancock & Warm, 1989), and when automated tracking removes the need for momentary attention, it is unlikely that performance level will be maintained. Automation of tracking provides the opportunity to scan the resource management display and develop and execute the changes needed to maintain target fuel levels, but it does not demand constant high levels of visual attention. Nor is the focus of attention during resource management in close physical proximity to the monitoring tasks. Automating one task decreases task load, but it cannot be assumed that time-sharing the remaining tasks will be accompanied by improvement in all performance measures. Similarly the self-reported fatigue increase during manual and automated tracking sessions suggests that the decreased subjective workload present during automated tracking does not decrease fatigue associated with the MATB.

The increased resource management error during manual tracking in the first experiment provides an ideal environment to explore flexible automation. Tracking requires continuous attention and resource management requires full attention for brief periods, making tracking and resource management difficult to time-share. The opportunity to automate tracking eliminates the need to simultaneously perform two apparently incompatible tasks: tracking and resource management. When flexible, operator-initiated automation was introduced into the experimental protocol, fewer than one half of the participants used automation even though it changed task load in a manner that would be expected to improve performance and decrease high subjective workloads. Although task load decreases during automation, shifting between manual and automatic tracking adds a further task, and deciding when to initiate automation may have been too difficult for participants with only 1 hr of training. When training was increased to 7 hr and the procedure used to switch tracking between manual and automation was simplified, 4 of the 5 participants adjusted task load by shifting between manual and automatic tracking. During the optional-tracking session, participants efficiently performed the tracking task for approximately 80% of the session, changed pump configurations more frequently than they did during manual tracking, and completed the resource management task more effectively than they did during the manual or automatic tracking conditions.

Unexpectedly, when tracking was automated for the entire session in the second experiment, resource management was not superior to manual tracking sessions due to high resource management error during the initial portion of the session. After the high resource management error level during the first half of the session, participants rapidly changed pumps settings, and error level decreased dramatically, a pattern that suggests complacency and inattention early in the session rather than a shortage of mental resources.

In conclusion, automating one task in a multitask environment changes vigilance, response strategies and performance patterns, but it cannot be assumed that the performance of all nonautomated tasks will improve or that decreased fatigue will be associated with decreases in subjective workload. Attentional changes produced by automating one task can facilitate or disrupt the performance of other tasks. The improved performance when operators could switch between automated and manual tracking suggests that in dynamic environments operator control of automation can be an effective method of avoiding performance deterioration caused by overload or underload.

SUMMARY AND CONCLUSIONS

At a surface level, the act of automating one component of a multiple-task environment represents a step toward simplicity. Such simplification of task demand should, it is argued, lead to reduced energetic load upon the operator and result in less stress, fatigue, and mental workload as it facilitates performance efficiency. Surface simplicity unfortunately masks a deeper complexity. Switching to automation becomes a source of demand. Automated tasks cannot be forgotten, but are metamorphosed into additional monitoring tasks. Even automated tasks have to be monitored, which can lead to an infinite regress, evoking the question *Quis custodiet ipsos custodes?* (Who will guard the guard themselves?) In addition to sharing between subtasks (macro trade-offs), we have evidence of periodicities within subtasks (micro trade-offs), which makes the distillation of performance efficiency difficult (Scallen, Duley, & Hancock, 1994). Consequently, the design decision to automate, not to automate, or to permit discretionary automation remains a complex one, but one that is very definitely human-centered (see Billings, 1991). The results suggest that in high, variable workload environments where workload periodically exceeds operator capacity, it should be possible to maintain operator supervision of all tasks during all operational phases by having operators invoke automation during high taskload periods. However, it cannot be assumed that operators will always effectively use optional automation. The method of shifting between manual control and automation, the operator's skill, and the operator's concept of the appropriate use of automation need to be explored to fully describe the potential of dynamic operator-invoked automation. The results also suggest that decreased operator fatigue cannot be assumed from operators' reports that less workload is present during automation and that in addition to workload measurement, task-induced fatigue assessment should be a component of system evaluation.

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