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DOT/FAA/AM-94/3

Office of Aviation Medicine
Washington, D.C. 20591

Automation and Cognition in Air Traffic Control: An Empirical Investigation

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February 1994

Final Report

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

U.S. Department
of Transportation
**Federal Aviation
Administration**

NOTICE

Technical Report Documentation Page

1. Report No. DOT/FAA/AM-94/3	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Automation and Cognition in Air Traffic Control: An Empirical Investigation		5. Report Date February 1994 6. Performing Organization Code
7. Author(s) O.U. Vortac, Mark B. Edwards, Dana K. Fuller, and Carol A. Manning		8. Performing Organization Report No.
9. Performing Organization Name and Address FAA Civil Aeromedical Institute P.O. Box 25082 Oklahoma City, OK 73125 University of Oklahoma Dept. of Psychology 755 W. Lindsey, Room 705 Norman, OK 73019-0535		10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFA-02-91-C-91089
12. Sponsoring Agency name and Address FAA Office of Aviation Medicine Federal Aviation Administration 800 Independence Avenue, SW. Washington, DC 20591 FAA Research and Development Service Federal Aviation Administration 800 Independence Avenue, S.W. Washington, DC 20591		13. Type of Report and Period Covered 14. Sponsoring Agency Code

15. Supplemental Notes

This work was performed under task AM-D-92-HRR-141 and Contract No. DTFA-02-91-C-91089

16. Abstract

Several investigators have expressed concern that the imminent automation of air traffic control may have negative consequences on cognitive functioning, and ultimately on performance. We investigated these possibilities empirically by comparing normal, conventional air traffic control with an experimental condition designed to resemble an extreme version of automation. Overall, measures of performance were comparable between conditions. Most of the cognitive measures (attentional demands, visual search, recall of flights, recall of flight data) were not impaired by the automation analog. Instead, two prospective measures (prospective memory, planning) showed improved performance. The prospective memory advantage is particularly surprising given that the automation-analog group was unable to manipulate external memory aids. Possible reasons for the prospective memory advantage include a reduced workload which allows the controller to get the necessary information in other ways, and a change in the nature of the task resulting from the "automation" of the strip management *module*.

17. Key Words Automation, Air Traffic Control, Flight Progress Data, Cognitive Psychology, Memory, Applied Psychology		18. Distribution Statement Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 21	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGMENTS

O. U. Vortac represents the collaborative efforts of Francis T. Durso, Scott D. Gronlund, and Stephan Lewandowsky, all at the Department of Psychology, University of Oklahoma, Norman, OK 73019-0535 (e-mail: ouvortac@oucog1.psy.uoknor.edu). This research was supported by Contract #DTFA-02-91-C-91089. We are grateful to the instructors and management, Gwen Sawyer, Manny Torres, Claude J. Schuldt, of the FAA Academy at the Mike Monroney Aeronautical Center, with special thanks to our subject matter expert, Tom Lynch. Thanks also to Fernando Ospina, Ron DeCost, Michael Moravec, Henry Smith-Mogilka, and A. J. Rotter. We wish to thank the following for their comments on an earlier version of this manuscript: Mitch Grossberg, Bill Collins, Doug Herrmann, Mike Wayda, and two anonymous reviewers.

AUTOMATION AND COGNITION IN AIR TRAFFIC CONTROL: AN EMPIRICAL INVESTIGATION

In recent years, the 17,000 civilian air traffic controllers in the United States have handled upward of 100 million aircraft operations annually. Further significant increases in traffic volume are expected over the next few years, which will place additional demands on the available airspace and will exact higher performance from air traffic controllers. To meet these traffic loads, far-reaching automation is scheduled for introduction into air traffic control (ATC) during the remainder of the 1990s. There is little doubt that automation is inevitable and, in the end, largely beneficial. Nonetheless, numerous potentially important concerns have been expressed about the psychological consequences of automation on air traffic controllers. These concerns typically revolve around the view that the manual performance of some tasks, although repetitive and burdensome, may be beneficial because it builds understanding relevant to overall performance. In this view, automation of routine activities may have unintended negative consequences for performance and, by implication, air traffic safety (e.g., Hopkin, 1988, 1989).

We have focused on the likely psychological consequences associated with the initial stage of automation of "en route" ATC (see Vortac & Gettys, 1991, for a review). Briefly, en route control handles the airspace between departure and arrival airports and corresponds approximately to the high-speed and high-altitude cruise between takeoff and landing.[1] En route control is distributed across some 20 ATC centers in the continental United States, each of which is responsible for a large segment of airspace. The airspace assigned to an en route center, in turn, is carved into multiple sectors, each handled by a controller or, if required by traffic loads, by a team of two or more controllers.

Currently, en route control relies on three primary tools: Computer-enhanced radar information displayed on the plan view display (PVD), communication devices (radio and telephone), and flight progress strips (FPSs). FPSs consist of small rectangular pieces of paper containing up to 31 pieces of flight data (e.g., call sign, aircraft type, assigned altitude, route of flight, etc.) that augment the information obtainable from the PVD. (See Figure 1.)

In the field, each flight is typically represented by a unique FPS, printed prior to entry into the sector and based primarily on the flight plan filed before take-off. Strips are mounted in plastic holders that are stacked, usually by arrival times, in ascending chronological order in a posting board or "bay" located next to the radar display. Flights about to enter a sector are posted in a suspense bay; once a flight becomes active by entering the controller's sector, its strip is moved to the adjacent active bay. While a flight is active, the controller frequently interacts with the corresponding FPS on the board by writing on the strip itself to update the speed, the altitude, the route, or by moving the FPS within the active bay. Figure 1 shows the difference between a strip immediately before a plane enters the controller's sector and that same heavily marked strip after the controller has taken a number of actions involving that aircraft. Some of these markings are due to the controller's legal obligation to use the strip as a legal record of the flight. Thus, while controllers interact with the paper FPSs at least part of this interaction is because it is mandated. The question remains whether this mandated activity has coincidental cognitive and performance benefits.

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[1] Different phases of a typical flight are handled by a number of different air traffic control facilities. Ground control separates aircraft as they taxi from the gate to the active runway. Local control grants permission to enter an active runway, and then handles takeoff and initial climb-out to (typically) 3,000 feet. From this point out to within 50 nautical miles of the airport is the domain of the Terminal Radar Approach Control (TRACON). The remaining airspace is the domain of en route control, which includes arrivals and departures from uncontrolled airports.

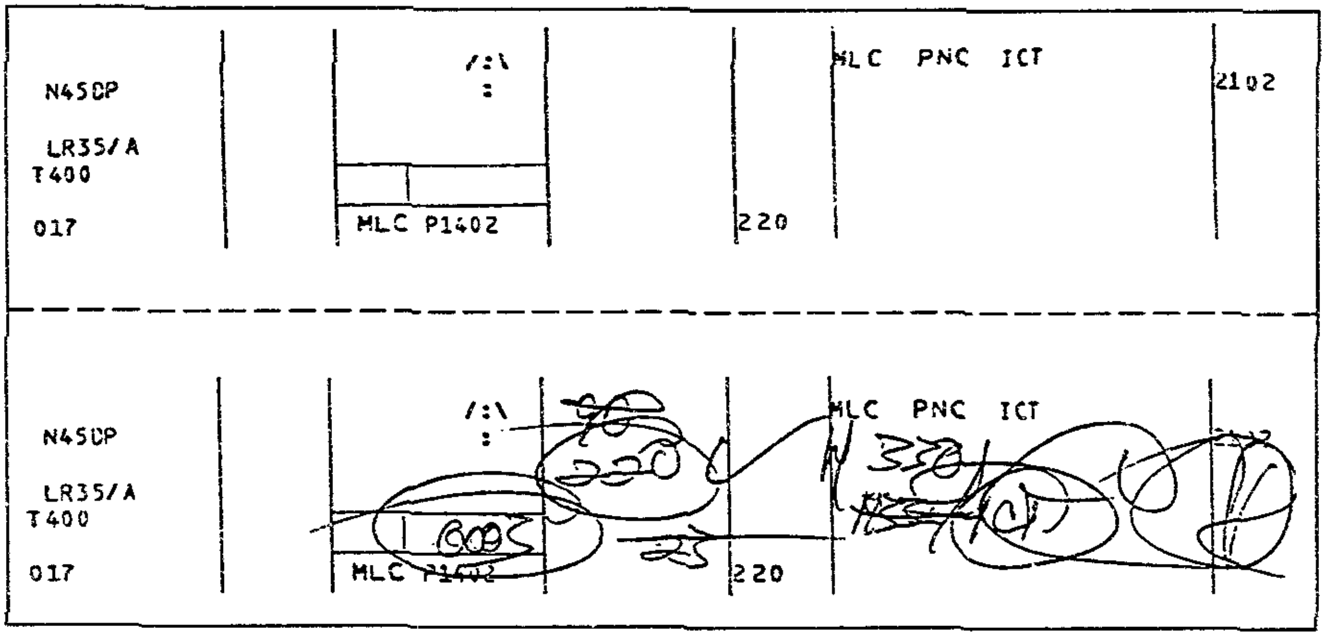

Figure 1. A flight progress strip for a flight, before it enters the controller's sector (top) and after it has been active in the controller's sector (bottom).

The first stage of en route automation, the Initial Sector Suite System (ISSS), has its most dramatic effect on the FPS. Under ISSS, FPSs will be replaced by entries on a large electronic display located next to an improved, colorized version of the PVD. Controllers will interact with flight data in an indirect manner through a keyboard, rather than by direct physical manipulation and updating of an FPS. Moreover, numerous current strip-related activities (e.g., moving strips between bays) will be obviated by electronic processes (e.g., automatic posting of strips). Finally, less information is expected to be shown on the electronic displays than is currently visible on paper strips.

Concerns have been voiced about the impending removal of paper flight strips, based on the possibility that some of their unique and potentially beneficial properties might not be fully embodied in the new electronic system. In particular, it has been claimed that the strips may embody important communicative purposes (Shapiro, Hughes, Randall, & Harper, 1991), that they serve as a memory aid (e.g., Hopkin, 1989, 1991; Jackson, 1989), that they are important external retrieval aids, and that they support cognitive processes in numerous additional ways (for a review see Vortac & Gettys, 1991). It thus stands to reason that the conversion from paper FPSs to electronic displays may have adverse cognitive consequences. However, like other assertions surrounding automation, the exact role of the strips has not been resolved by empirical testing.

One reason for this paucity of research may be the difficulty in determining the exact final functionality of the automation that will replace the paper FPSs (Nordall, 1993). Although the general framework for the new system has long been determined (Ammerman & Jones, 1988), considerable debate continues to revolve around the optimal format in ISSS for the new electronic "strips." To accommodate this design uncertainty without compromising a meaningful test of the likely consequences of ISSS, the experimental manipulation reported here was chosen to be *more extreme* in its potential cognitive consequences than the anticipated automation.

We observed controllers under one of two conditions: Subjects in the automation-analog (Restricted) condition were given limited information on their strips, and they could not move or write on them. The control (Normal) subjects had full access to unmodified strips. Hence, the results of the present experiment should be interpreted as an *upper bound* on the cognitive changes attributable to interaction with FPSs.

In addition to measuring subjects' air traffic control performance, the experiment also involved a variety of cognitive measures. Cognitive measures are often more sensitive than conventional performance measures; this is particularly true in ATC where serious procedural errors and other overt performance deficits are extremely rare. Hence, well-chosen cognitive measures may serve to identify deficiencies before they result in rare—but nonetheless catastrophic—failures.

We now identify cognitive processes likely to be affected by the automation of flight strips, thus measured in our experiment. A comprehensive review of the role of cognitive processes in air traffic control, going beyond the role of FPSs, is provided by Cox (1992).

Attention

Attentional engagement. An important part of assessing the impact from a cognitive perspective of any automation is to determine if the automation affects the extent to which the controller is attentionally engaged in the primary task of controlling air traffic. In psychology, momentary processing capacity is commonly measured by a secondary probe task in which latency to respond to some secondary (i.e., less important) stimulus is thought to reflect the amount of attentional capacity devoted to the primary task (Baddeley & Hitch, 1974). Estimates of capacity demand for any particular task depend on particular characteristics of the probe task (McLeod, 1977, 1978) and thus the latency to respond reflects the cost of attentional *dis*engagement from the primary task (Allport, 1989). Response time to the probe is slow when a high level of selective attention is necessary to maintain the integrity of the primary task.

Thus it is important not to view the secondary probe as providing a passive indirect measure of processing capacity of the primary task. To assess engagement from such a task, it is important that the probe be part of the high fidelity simulation. Fortunately, in ATC, responding to telephone calls from adjacent centers is a routine component of controlling traffic, giving us a naturalistic secondary probe and an uncorrupted measure of the cost of attentional engagement.

Visual search. Automation of FPSs is likely to influence visual search rate. Visual search involves allocation of limited attentional resources, in order to select from a number of potential inputs, the stimulus to be attended (Johnston & Dark, 1986; Shiffrin, 1988). When incoming information can be processed with little attentional processing, it appears to "pop-out" from the background (Treisman & Gelade, 1980). An FPS that has been marked extensively is visually distinctive and may pop out from among the other strips (Figure 1). For example, if assigned altitude is changed, the controller crosses out the original value and writes in the new altitude underneath. Often, a flight will require a number of such changes; their cumulative effect being a visually unique strip that can be more easily located in the strip bay (Jackson, 1989). Under automation, however, all the electronic strips will look much the same; the history will not be maintained (at this writing, under the operative design for ISSS, flight history appears to be limited to the preservation of the last preceding entry, and the computer forces standardization in appearance.) This may slow search of the strip bay under automation, where an automatic "pop-out" of the visually distinctive information might have occurred previously.

Search may also be aided because the controller actively organizes the constellation of strips. Under automation any subjective organization may be eliminated or made more difficult. Certainly under the automation-analog we consider here the controller had no impact on the organization of the FPSs.

Retrospective Memory

Retrospective memory is memory for past information and actions (for a recent review see Baddeley, 1990). The importance of past episodic events (e.g., clearances, the history of the flight, presence of weather) suggests that good retrospective memory will facilitate controller performance in numerous ways (for a review see Vingelis, Schaeffer, Stringer, Gromelski, & Ahmed, 1990).

Direct involvement. Memory is better for information that a person generates or action a person takes, as opposed to information a person perceives or actions that a person observes being done (e.g., Slamecka & Graf, 1978). In the current system, from the time that an FPS is printed to the time that it is removed from the bay, the controller is directly interacting with the FPS. The nature of the controller's direct interaction with the strip is thought to result in improved incidental memory for flight information: "The controller might offset a particular flight strip within the flight strip board as a memory aid. The fact that the action was under the controller's own initiative helped the controller recall why it had been taken and what had to be remembered." (Hopkin, 1989, p. 1639). Under automation, many of these operations will be done by computer.

Organization. Placing a strip at a particular place in the bay when a flight enters the controller's sector enhances organizational and relational aspects of memory for the flight data (Bower, 1970; Mandler, 1961) by emphasizing similarities among aircraft (e.g., going to the same destination, at the same altitude). Also important is the encoding of distinctive information; for example, noticing that a plane is behind schedule or at a lower than expected altitude. Under automation, the computer will automatically place strips in the bay, possibly impairing the encoding of relational and distinctive information.

Furthermore, the controller is currently responsible for reorganizing the order of FPSs to reflect the changing conceptual structure of the traffic situation. Under automation, much of this reorganization will be done for the controller. Organization has perhaps the greatest potential for improving memory performance, and thus any reduced amount for harming memory performance.

Cuing. Gromelski, Davidson, and Stein (1992) collected and cataloged controller memory aids. The three memory aids used most often all involved strips: 1) arrangement of strips in a logical manner; 2) offsetting strips; 3) marking. It may prove difficult to use the electronic equivalent of the strips as a memory aid or cue that is cognitively equivalent to paper FPSs.

Intons-Peterson and Fournier (1986) studied the use and effectiveness of external and internal memory aids. External memory aids are preferred for spatial tasks, in our case, presumably, for the position of aircraft on the two dimensional PVD. Although "paper strip equivalents" will be available in the automated system, lost functionality may make them less effective external cues.

In fact, an experiment by Lansdale, Simpson, and Stroud (1990) supports exactly this idea. Lansdale et al. had subjects perform a filing task in which each item of information was to be annotated for later retrieval. These annotations were either generated by the computer or composed by the subject. The latter condition led to improved memory. By analogy, "marking" on electronic strips will be much more restrictive than marking on paper strips. Extrapolating the results of the Lansdale et al. study suggests that this restriction may hamper memory by reducing the effectiveness of the external cues.

Prospective Memory and Planning

In addition to facilitating the recollection of past events, it has been argued that flight strips support prospective memory through their use as external memory aids (Vortac & Gettys, 1991). Prospective memory is the use of memory to remember to take a planned action at a future time. This is essential in air traffic control, with controllers having to remember to return to earlier clearance requests, or having to conform to plans made earlier.

In comparison to retrospective memory, prospective memory has been little researched (Harris, 1984), although that is beginning to change, especially in light of the results that show that the two types of memory are uncorrelated (e.g., Einstein & McDaniel, 1990; Kvavilashvili, 1987; Meacham & Leiman, 1975; Wilkins & Baddeley, 1978; but see Hitch & Ferguson, 1991). In fact, some of the work is quite provocative from the perspective of the current paper: For example, the Intons-Peterson and Fournier (1986) study cited earlier showed that external memory cues are preferred for future remembering.

Distinctiveness. Distinctiveness or unfamiliarity of an external cue has been found to result in superior prospective memory performance (Einstein & McDaniel, 1990). A paper strip is distinctive either by the amount and kind of idiosyncratic marking done by the controller or by being physically offset from the others in the bay. Because automation will force standardization and thereby lessen distinctiveness (as discussed earlier), the electronic equivalents of paper FPSs may not be as distinctive and may therefore be a relatively poor prospective memory cue.

Motoric enactment. Koriat, Ben-Zur, and Nussbaum (1990) found that motoric enactment of future actions (e.g., lift one object, replace another) improved prospective memory, compared to verbal rehearsal. A conceivable implication is that the automated system, which cannot support any distinct motoric component because input is done through the keyboard or trackball, may support prospective memory less efficiently than the current paper strip system.

METHOD

Experimental Automation Analog

The FPSs used in the experimental (Restricted) condition showed only 4 of the usual 31 pieces of flight data: call sign, aircraft type, assigned altitude, and route. In addition, the strip holders were glued together and subjects were not permitted to touch, move, write on, or manipulate them in any way. The Restricted condition was compared to the Normal condition, in which subjects had full access—including writing and manipulating—to the complete currently-used strips.

The Restricted condition provided an experimental analog to ISSS in several ways: First, the amount of information remaining on the skeleton strips approximated a minimal version of the electronic displays currently under consideration. Second, the less direct interactive nature of the electronic display was mimicked by restricting the controller's ability to move strips. Other methods for retrieving flight data available on the system were left intact. For example, controllers had the option of retrieving further flight information from the computer via additional keyboard interaction.

Subjects

A total of 20 subjects participated, with 10 subjects randomly assigned to each group. All subjects were instructors at the FAA Academy, and comprised a nearly exhaustive sample of that population. All were full-performance level controllers who had been en route controllers for an average of 6.7 years, and last served in the field 17 months prior to the study. Eight of the subjects had participated in an earlier observational study conducted by the same research team (Vortac, Edwards, Jones, Manning, & Rotter, in press).

Each subject participated individually in two scenarios of medium complexity. The first scenario was used to obtain performance measures. The second scenario was run in two segments, separated by a battery of cognitive tasks.

Materials

The experiment was conducted at the en route Radar Training Facility (RTF) at the FAA's Mike Monroney Aeronautical Center in Oklahoma City, which provides high-fidelity air traffic simulations using the fictitious AeroCenter airspace used in Academy training. All subjects were instructors familiar with AeroCenter.

Two experimenters were present throughout each experimental session. In addition, a subject matter expert (acting manager of the RTF or a designated substitute) was present during the first scenario to assess controller performance and to assume the role of supervisor. Two "ghost pilots" controlled the planes, and another ghost assumed the communication functions of adjacent Centers and other ATC facilities.

Two scenarios of medium complexity (6.5 departures, 10.5 arrivals, and 11.5 overflights on average) unfamiliar to the Academy instructors were selected with the help of our subject matter expert. Each scenario lasted approximately 30 minutes and involved levels of traffic density that in the field could be handled by an individual.

Procedure

Prior to a subject's arrival at the RTF, all FPSs were placed in the strip bay (located to the right of the radar) sorted in ascending order by time of arrival or departure. The strip bay was then covered.

Subjects first completed a background questionnaire. The subject matter expert then familiarized participants with the letters of agreement, handoff procedures, and radio frequencies relevant to the scenario. All subjects were familiar with AeroCenter, but some had been accustomed to controlling AeroCenter traffic using non-radar procedures and needed familiarization with specific procedures for radar ATC.

Instructions were then given regarding the Normal or Restricted condition. The normal group was given 5 minutes to set up and inspect the FPSs, and the restricted group received the same amount of time to inspect the FPSs. The Normal group was told they could arrange and write on the FPSs as they normally would in the field; the Restricted group was told they could only look at the (limited) FPSs. The scenario started when subjects indicated that they had inspected the strip bay to their satisfaction, or when the maximum time of 5 minutes had elapsed.

During the scenario, an audio record was kept of the controller and the ghost pilots. The subject's interactions with the Quick Action Keyboard (QAK) on the radar console were recorded. Some of the keys on the QAK can be used to replace FPS functionality: For example, one key provides a display of an aircraft's route on the radar, and another one prints out the complete flight plan on the Computer Readout Display (CRD; a small screen next to the radar). The frequency with which these keys are pressed thus provides an index of the extent to which a subject replaced an interaction with a flight strip with a computer interaction. In addition, during the scenario, the experimenter recorded the number of commands controllers issued and the number of requests made by the controllers. These two controller activities were intended to provide a measure of any gross differences in how the groups differed in their interaction with the air traffic.

Scenario I (Performance Measures)

Assessment of ATC performance is a non-trivial task. Buckley, DeBaryshe, Hitchner, and Kohn (1983) examined some 28 possible indices, among them fuel consumption, delays, and subjective variables (e.g., performance rating by subject matter experts). Buckley et al. suggested that a combination of both subjective and objective measures is required for a full performance assessment. Hence, the present experiment included (i) standard "over-the-shoulder" evaluation by a subject matter expert, (ii) on-line evaluation of a position relief briefing by the same expert, and (iii) a quasi-objective post-scenario analysis of the traffic pattern.

"Over-the-shoulder" evaluation. "Over-the-shoulder" evaluation was conducted by the subject matter expert, using the FAA's On the Job Training evaluation form (OJT; FAA Form 3120-25). The OJT form has several items directed at five aspects of ATC performance: Separation, control judgment, methods/procedures, equipment, and communication/coordination.

Position relief briefing. Twenty-one minutes into the first scenario, the subject matter expert requested an unanticipated position-relief briefing. The position-relief briefing was conducted as in the field when one controller provides information relevant for the relieving controller to take over the control of the sector. The quality of the briefing was assessed using a position-relief briefing checklist which contained several items that queried the completeness of actions dealing with traffic and non-traffic aspects of the current situation.

Post-scenario analysis. The scenario was terminated at 27 minutes, and after the subject had left the laboratory, the subject matter expert analyzed the traffic pattern and decided, for each aircraft on the PVD, how many route, speed, or altitude changes (if any) remained to be taken to get the plane out of the controller's sector. Given the same set of initial conditions and a constant amount of elapsed time, the more efficient controller should have fewer control actions remaining for a given aircraft than the less efficient controller. We consider this a quasi-objective measure because, for a subject matter expert, there is little uncertainty about what actions are required for a given aircraft before it is handed over to an adjacent facility.

Scenario II (Cognitive Measures)

The two scenarios were separated by a 15-minute break period. Subjects followed the same bay inspection procedure for the second scenario and no additional instructions were given. The prospective memory and attention measures were taken unobtrusively during the scenario.

Prospective Memory. Prospective memory was tested by incorporating pilot requests to which the controller could not immediately respond. On three separate occasions, pilots made a request before their aircraft had entered the controller's airspace. Because the aircraft were then still under the adjacent sector's control, the controller had to tell the pilot to standby and had to remember to reply to the initial request after the plane had entered the sector. (Another legal option for the controller would have been to call the adjacent sector for permission to get control immediately, in order to deal with the situation on the spot. These requests were always denied.) Specifically, at 3:02 minutes into the scenario, a general aviation flight requested to be vectored around weather; at 9:30 a commercial flight requested a lower altitude; and at 18:15 a military flight requested direct routing to Kansas City.

Attentional Engagement and Visual Search. Seven measurements of attentional load were obtained during the scenario by ringing the land line (telephone) from an adjacent center. Time was measured, using the audio record, from the first ring until the subject answered. On two occasions, when the controller answered the land line he or she was asked whether an FPS for a particular aircraft was present. In both cases, the strip was absent, necessitating an exhaustive search of the strip bays. The subsequent latency to scan the strip bay—defined as the delay to answer the request—provided an index of visual search times.

At the 16-minute mark, the scenario was temporarily suspended. At this point, 13 aircraft were visible on the PVD: five commercial, five general aviation, and three military. Three of these had very recently appeared on the screen and were not yet in the controller's sector. The controller was instructed to turn away from the radar and the remaining battery of cognitive tests was administered.

Map Recall. The controller was instructed to recall the positions (with call signs if possible), of all controlled aircraft by marking the appropriate locations on a clear sheet of plastic. The sheet contained sector boundaries, jetways, and other landmarks used on the radar, as shown in Figure 2. Six minutes were allowed for Map Recall.

Cued FPS Recall. Subjects were then given a test booklet containing one FPS to a page, with only the call sign provided. FPSs were arranged in a different random order for each subject, and recall of three fields on each strip (aircraft type, altitude, and route) was cued by a '?' symbol. Subjects were instructed to proceed through the booklet in order, without skipping pages or returning to previous strips and to complete as many of the cued fields as possible. They were given 10 minutes to complete this task. Upon completion of the first pass through the test booklet, subjects were given a different color pen and asked to recall any additional information they might remember about the flights. Subjects could work through the booklet in any order on the second pass. They were given six additional minutes to complete this task.

Traffic Planning. Finally, subjects were turned back toward the PVD and allowed to look at the radar and the strips. The PVD was covered with a clear sheet of plastic and subjects were asked to draw the anticipated exact flight path for all flights for the next 10 minutes. They were told that the scenario would be re-run after the experiment to measure conformance between actual and planned flight paths. Upon completion of the traffic planning task, the scenario resumed for the remaining 14 minutes without any further interruptions.

RESULTS

Analysis of each set of measures began with an omnibus multivariate, Pillai's trace (MANOVA) or univariate analysis of variance (ANOVA); significant omnibus tests justified subsequent univariate tests and contrasts. All tests used α = .05 unless otherwise indicated. Measures of performance and control actions were from the uninterrupted first scenario; measures of cognition and flight strip use were from the interrupted second scenario.

Control actions

A MANOVA indicated that controllers with restricted access to limited strips were similar to controllers with normal access to the strips in the number of verbal commands issued (M = 57.8 and 52.6, for Normal and Restricted, respectively) and in the number of requests uttered (M = 11.5 and 8.0, for Normal and Restricted, respectively).

The frequency of QAK keys pressed (i.e., flight plan readout, assigned altitude, interim altitude, and route projection) were analyzed for nine subjects in each condition. (Scenario summaries for one subject in each condition were lost due to equipment malfunction.) A MANOVA [$F(4,13)=1.55$] showed that the two groups of controllers made similar use of the QAK (see Table 1). The apparently large difference between the groups on the use of the flight plan readout key was caused by one subject in the Restricted condition using the key over 25 times, inflating the mean and variability for that group. Thus, both in terms of the frequency of commands and in the controller's interactions with the QAK, the restriction placed on the strips did not reliably alter interaction with the air traffic or the computer.[2]

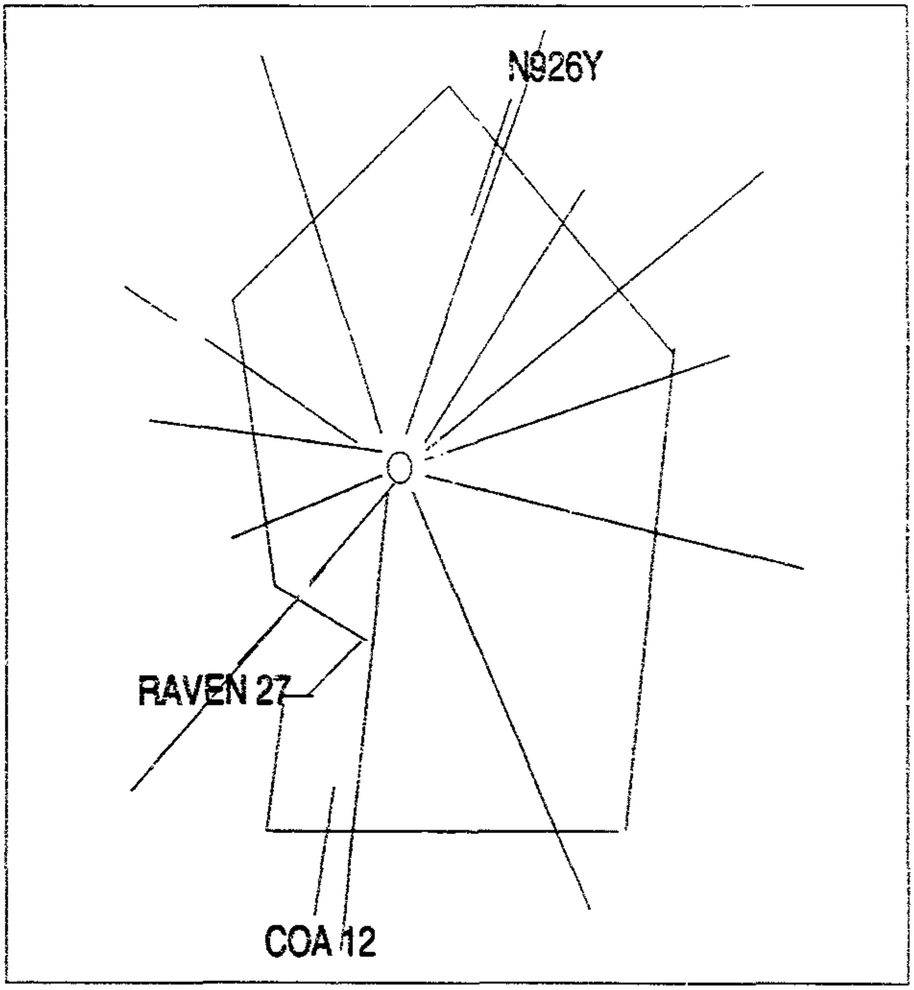

Figure 2. Sector map used during Map Recall. Subjects marked the recalled locations of all aircraft together with their call sign.

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[2] All analyses reported in this article were conducted without the subject in the restricted condition who appeared to compensate for the limited strips by using the QAK and without the subject in the normal condition who chose not to mark the FPS's. We thought that including these subjects might reduce the difference between the experimental condition and the control condition, thus masking a possible effect of restricting access. The additional analyses supplied no support for this concern, and thus we report only those analyses that included all of the subjects.

Table 1

Frequency of quick action key presses

Condition	Key	Mean	Std. Deviation
Normal	Flight Plan	1.78	2.86
	Assigned Altitude	5.67	3.04
	Interim Altitude	10.67	8.79
	Route	13.56	9.19
Restricted	Flight Plan	6.33	8.93
	Assigned Altitude	4.78	3.23
	Interim Altitude	7.89	4.91
	Route	8.44	4.90

Table 2

Frequency of negative performance comments, OJT Form

Condition	Performance Class	Mean	Std. Deviation
Normal	Separation	0.50	0.53
	Control Judgment	2.10	1.60
	Methods/Procedures	2.50	1.43
	Equipment	0.00	0.00
	Communication/Coordination	0.40	0.52
Restricted	Separation	0.40	0.70
	Control Judgment	2.00	1.89
	Methods/Procedures	1.50	1.90
	Equipment	0.10	0.32
	Communication/Coordination	0.80	1.13

Flight Strip Use

To verify that subjects in the Normal condition interacted with flight strips, the number of markings and changes made on the FPSs during the second scenario was analyzed. The average number of markings on all strips was 126.6, with a maximum of 216 and a minimum of 1. Hence, only one subject in the Normal group chose not to mark on the FPSs (the second-lowest number was 84), suggesting that most controllers in the Normal condition interacted with strips in the manner expected in the field.[2]

Performance

OJT Form

The number of negative comments made by the subject matter expert was tabulated for each major section of the OJT form (see Table 2). A MANOVA indicated that judged performance under the Restricted condition was comparable to performance under the Normal condition [$F(5,14)<1$].

Position-Relief Briefing

The proportions of both traffic and nontraffic items covered satisfactorily in the position-relief briefing were computed. A MANOVA on these two variables again indicated no difference in performance between the Restricted and Normal conditions [F (2,16)<1]. Normal controllers covered 74% of the traffic items and 44% of the nontraffic items satisfactorily; Restricted controllers covered 80% of the traffic items and 33% of the nontraffic items satisfactorily.

Post-Scenario analysis

We tabulated separately the number of route, altitude, and speed changes the subject matter experts indicated were remaining to be performed at the end of the scenario. The MANOVA revealed that controllers in the Restricted condition tended to have more actions yet to be performed than did those in the Normal condition, F (3, 16) = 2.45, p = .10. Although the effect was not significant by the .05 criterion, the importance of a possible performance decrement dictated that any potential effect, however slight, was worthy of further consideration. Thus, subsequent univariate ANOVAs were conducted. These tests indicated that the difference between conditions was due entirely to the controllers in the Normal condition having initiated more required route changes than did those in the Restricted condition [F (1, 18) = 5.31], whereas no differences were found for required speed [F (1,18) < 1] and altitude [F (1,18) = 1.29] changes. On average, controllers in the Restricted condition had 1.1 more route changes remaining than controllers in the Normal condition.

Summary of Performance Measures

Overall, the performance measures suggest that controllers in the Restricted condition controlled traffic as well as those under Normal conditions. The only suggestion of a performance deficit was a small *univariate* effect in the number of route changes remaining.

Cognitive measures

Attentional measures

Data were analyzed separately for the time to answer the land line and the time to search the strip bay. Mean latencies were computed for each subject across the seven land line calls. An AWS t-test (e.g., Winer, Brown, & Michels, 1991) revealed no difference between Normal (M = 23.1 s) and Restricted (M = 27.7 s), suggesting that attentional demands of controlling traffic were comparable under the two conditions.

Mean latencies to deny the existence of the requested strip were computed for each subject across the two opportunities. These latencies were corrected for the number of strips currently in the bay when the request was made, yielding a time per strip. (This was necessary because the Normal group could remove unnecessary strips and so had fewer through which to search). Again, the AWS t revealed no difference between the two conditions, indicating that controllers could search a strip bay they could not manipulate (M = .624 s/strip) as quickly as they could search a strip bay they had organized (M = .603 s/strip).

Retrospective memory

Two datasets were created to investigate retrospective memory. One dataset drawn from Map Recall comprised the number of aircraft correctly placed on the sector map and the missed-distance (in cm) of those placements (see Table 3). The other dataset from Cued FPS Recall comprised the proportion of correct recall averaged across all relevant strips for each subject, of the aircraft type, altitude upon sector entry, route, and destination (see Table 4). Only one subject added additional flight data on the second attempt, and thus only the first attempt at recall was analyzed. In addition to comparing Normal and Restricted access, these MANOVAs divided aircraft into commercial (there were five on the screen), military (three), and general aviation (five).

The analysis of the Map Recall dataset failed to reveal a difference between conditions, with those in the Normal condition recalling 30% of the aircraft with their proper call sign and those in the Restricted condition recalling 44% of the aircraft with their call signs [F (2,17)=1.57]. The low absolute level of performance was due to the requirement that the correct call sign be affixed to a target placed on the sector map. When targets are counted without regard to accuracy of call sign, the recall levels were 63% and 75% for Normal and Restricted, respectively. Although

Table 3

Map Recall Performance

Condition	Type of Aircraft	Proportion Recalled		Missed Distance (cm)	
		Mean	Std. Dev.	Mean	Std. Dev.
Normal	Commercial	.50	.30	2.17	1.25
	General Aviation	.08	.17	3.83	2.23
	Military	.33	.00	2.02	1.24
Restricted	Commercial	.64	.35	2.25	2.04
	General Aviation	.28	.23	2.17	1.65
	Military	.40	.21	3.16	3.38

Table 4

FPS Recall Performance

History of Aircraft	Condition	Type of Aircraft	Mean Proportion Recalled			
			A/C Type	Altitude	Route	Destination
Currently on PVD	Normal	Commercial	0.12	0.38	0.12	0.42
		General Aviation	0.05	0.04	0.12	0.14
		Military	0.11	0.28	0.10	0.03
		M	*0.09*	*0.23*	*0.11*	*0.20*
	Restricted	Commercial	0.12	0.42	0.18	0.48
		General Aviation	0.07	0.06	0.12	0.14
		Military	0.11	0.26	0.03	0.10
		M	*0.10*	*0.25*	*0.11*	*0.24*
No longer on PVD	Normal	Commercial	0.00	0.13	0.23	0.23
		General Aviation	0.03	0.00	0.13	0.07
		Military	0.06	0.36	0.23	0.00
		M	*0.03*	*0.17*	*0.20*	*0.10*
	Restricted	Commercial	0.07	.13	0.23	0.30
		General Aviation	0.00	0.00	0.13	0.07
		Military	0.06	0.36	0.17	0.00
		M	*0.04*	*0.17*	*0.18*	*0.12*

insignificant, it is worth noting that recall is in a direction opposite that expected by those concerned that less interaction with the strips would reduce memory.

The type of aircraft had a large overall effect; $F(4, 72) = 6.45$. Exploration of the effect by multiple correlated-groups *t*-tests revealed that commercial planes were recalled better than military, $t(18) = 2.90$, or general aviation aircraft, $t(18) = 6.09$, and military were recalled better than general aviation, $t(18) = 4.03$. This effect appeared only in the number of call signs placed on the map, not in the missed-distance of the recalled flights [$F(2,38) < 1$]. The effect of flight class on memory is consistent with the preponderance of commercial flights, but the absence of an interaction of condition with flight-class also indicates that limited access to the strips did not affect this relative ordering.

Unlike the Map Recall data, the Cued FPS Recall included planes that had not yet appeared on the PVD and planes that had left the PVD, as well as those planes currently visible. We performed a separate analysis on each set of strips. Recall of flight data for future flights was essentially zero for all controllers. For past and current flights there were no differences between Restricted and Normal access to strips. However, as with Map Recall, the class of flight did yield significant multivariate *F*s (current flights: $F(8,68) = 9.32$, and past: $F(8, 68) = 9.67$]. Recall of the flight's destination was better for commercial than military flights ($t(18) = 6.84$ for past and $t(18) = 6.03$ for current) and general aviation flights ($t(18) = 3.94$ for past and $t(18) = 4.41$ for current). Destinations of general aviation flights, in turn, were recalled better than those of military flights ($t(18) = 2.18$ for past and $t(18) = 2.10$ for current). Again, limited access to flight data did not affect the ordering between classes of flights suggesting that retrospective memory may be relatively immune to the types of automation changes captured here.

Prospective Memory

The prospective memory data (see Figure 3) comprised the number of pilot requests that were ultimately granted, as well as the delay before those requests were granted. The MANOVA showed reliable differences between groups, $F(2, 17) = 4.34$, and the subsequent ANOVAs showed that the effect was due to controllers in the Restricted condition remembering to grant *more* requests, $t(18) = 2.35$, and tending to grant them sooner than controllers in the Normal condition, $t(18) = 1.93$, $p = .07$.

Planning

The planning data (see Table 5) comprised the number of turns executed (or not executed) during the 10 minutes following resumption of the second scenario, compared to the number of turns previously planned. The planning data were based on five aircraft for each subject. Three of these aircraft had just appeared on the PVD and were about to enter the controller's sector. Of all the other flights on the PVD, only two clearly required route changes or turns within the next 10 minutes. For these five planes, we first determined if the subject had correctly indicated the true heading, plus or minus 30 degrees. This restriction ensured that the starting point for the controllers' plans and the actual state of the airspace were similar. This, in turn, allowed us to match planned turns with turns actually ordered when the scenario resumed. This criterion yielded a total of 35 and 36 usable observations for the Normal and Restricted condition, respectively, out of a total possible of 50 for each condition (5 flights x 10 subjects). The classifications into possible outcomes is shown in Table 5.

As with prospective memory, the planning data can also be viewed to be suggestive of a Restricted-condition superiority. An independent-groups *t*-test indicated that subjects in the Restricted condition anticipated significantly more (80%: 16/20) of subsequently made turns than in the Normal condition (52%: 14/27; $t(18) = 3.12$).

Alternatively, focus may rest on the fact that the Normal controllers were more likely to change the route of aircraft *for which their initial plan failed to foresee any such changes* (65%: 13/20; see Table 5). This compares to the Restricted condition, where controllers performed considerably fewer such turns (24%: 4/17). Assuming that both conditions ultimately required the same number of turns, the difference may suggest that the Normal controllers detected necessary route corrections more quickly than the Restricted subjects. Note that this analysis is consistent with the effect observed in the post-scenario

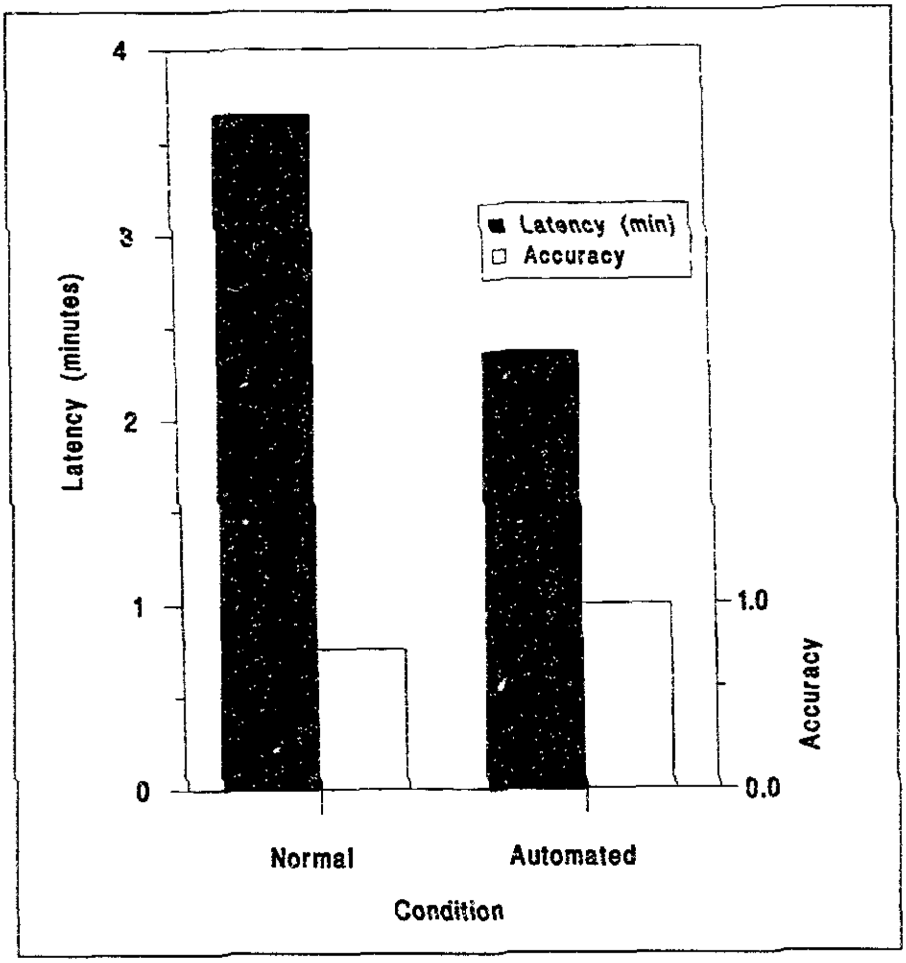

Figure 3. Prospective memory performance across the two conditions. Latency to comply with request is shown on the left-hand axis and accuracy (proportion compliance) on the right-hand axis.

Table 5
Frequency of Conformance and Non-conformance to Planned Actions

Condition	Action Planned	Action Taken		
		Turned	Not Turned	
Normal	Turned	14	1	*15*
	Not Turned	13	*7*	*20*
	Total	27	8	
Restricted	Turned	16	3	19
	Not Turned	4	13	*17*
	Total	*20*	*16*	

performance measure (Scenario I), where controllers in the Restricted condition had approximately one more route change remaining at the end of the scenario. Thus, although the greater proportion of anticipated turns speaks to better planning by controllers in the Restricted condition, this apparent superiority is accompanied by a tendency for Restricted-condition controllers to delay rerouting of some aircraft.

Summary of cognitive measures

Only prospective measures of cognitive functioning showed a difference between normal and limited access to FPSs, and those differences arguably favored the Restricted condition. The other measures confirm that this advantage of the Restricted condition was not due to a deficit elsewhere: The Restricted condition allowed comparably fast access to the land lines, equally speedy search of the strip bay, equivalent retrospective memory of aircraft positions, and comparable retrospective memory of the flight data.

DISCUSSION

Overall, contrary to the reasoning and literature cited at the outset, and contrary to speculations by aviation experts, reducing access to flight progress strips—in a manner more extreme than anything foreseen for ISSS—had little adverse effect on performance, and no measurable detrimental effect on the cognitive measures. In fact, the only effects reliable at conventional levels of significance involved forward-looking processes, prospective memory and planning, and favored the restricted condition.

It is true, however, that given the potentially catastrophic impact of even slight performance decrements in air traffic control, failure to reach conventional levels of significance should not deter other researchers from investigating further the possible negative impact of automation. Specifically, the suggestive result that controllers in the Restricted condition delayed necessary route changes (Scenario I) must be taken seriously. The effect was also arguably reflected in the planning data during the second scenario. In further support, consider the fact that pragmatic constraints limited the number of subjects to 10 in each condition, which may have prevented any subtle performance differences from reaching greater statistical reliability. On the other hand, the restricted condition was quite novel to our subjects and thus this deficit may be due to the novelty of the condition and not to the strip configuration. Also in line with this position is that any arguments based on lack of power must recognize that the nonsignificant effects do not tend to lean in favor of the normal condition as a power argument would imply. Overall, the performance data may be best interpreted as sounding a note of caution concerning the impending removal of flight strips that is worthy of further exploration.

As for the cognitive data, lack of statistical power cannot be invoked to explain the observed ***beneficial*** effects of restricted strip access on prospective memory. Restricted subjects were more likely to remember to grant a previously-delayed request, and complied with these requests sooner, than did controllers with normal access to the strips.

What might explain the superiority of the Restricted group? We propose two related reasons, involving (i) a reduction in workload, and (ii) a change in the structure of the task that induced a more strategic behavior.

Given the prospective memory literature and the data and thinking suggesting that FPSs were useful external memory aids (e.g., Gromelski et al., 1992; Vingelis et al., 1990; Vortac & Gettys, 1991) we expected the Normal group to have shown better prospective memory than the Restricted group. However, normal use of the strips carries with it the responsibility of performing the required strip markings and physical manipulations. Thus, in normal use the strip plays multiple roles, including its role of legal record with its mandated marking and board management responsibilities. Compared to these responsibilities, even an effective memory aid would be difficult to confirm. The Restricted group, freed from the workload of maintaining the strips, may have been able to focus in a more optimal fashion on the most relevant information, thus more than compensating for the lost memory aids.

Although the reduced-workload hypothesis is clearly plausible, it is unlikely to explain the prospective memory effect entirely on its own. For example, reduced workload should have been evidenced by the

Restricted group responding to the secondary probe more quickly, but the small effect is, if anything, in the opposite direction.

If workload alone cannot account for the effect of improved prospective memory, what may? Why in the current experiment should not having to keep a legal record manifest its benefits in prospective memory? We are currently working on the hypothesis that the capacity freed by eliminating or automating board management and legal maintenance allow the controller to take a more strategic view of the air traffic. This strategic view is consistent with controllers doing better in planning and prospective memory, as we have shown here, but it also implies other as yet untested hypotheses. For example, a controller in a strategic, as opposed to tactical or reactive mode, should be able to see conflictions of aircraft further into the future, should be better able to identify plausible future traffic configurations, and should be better at adjusting to unexpected traffic situations. The degree to which the static paper strip can serve as an aid for these processes may not be much beyond that supplied by watching the data block move in real time on the PVD. Unfortunately it is difficult to reconcile in any definitive way the discrepancy between our finding and the existing prospective memory literature until more work is done on prospective memory (e.g., expertise, dynamic tasks, analogical depictions) and on air traffic control (e.g., cognitive reallocation of resources, effect of automating particular subcomponents).

Conclusion

One consequence of ISSS will be a reduction in the amount of direct manual interactions with the flight progress strips. Overall, it seems that a severe reduction in direct interactions with flight progress strips will not have dramatic negative consequences, and may, in fact, have some positive ones: Relieving controllers of board management responsibilities will not adversely affect attention and retrospective memory, and will have a positive effect on at least some manifestations of prospective memory and perhaps planning. The current results also suggest that research and thinking designed to anticipate negative effects of automation should look more carefully at issues relating to the integration of sub-tasks within the overall flow of task activities. Although this research bodes well for correctly-engineered automation, similar studies should use controllers other than Academy instructors, should use scenarios for airspace sectors at other en route centers, and should attempt to compare specific implementations of the automation (e.g., ISSS) when it becomes available. Until then, the current research suggests that less interactions with flight progress strips should not be viewed as a large handicap and could instead enhance the controller's ability to consider future events.

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☆U.S. GOVERNMENT PRINTING OFFICE: 1994 - 560-063/80194