Technological developments have made it possible to automate more and more functions on the commercial aviation flight deck and in other dynamic high-consequence domains. This increase in the degrees of freedom in design has shifted questions away from narrow technological feasibility. Many concerned groups, from designers and operators to regulators and researchers, have begun to ask questions about how we should use the possibilities afforded by technology skillfully to support and expand human performance. In this article, we report on an experimental study that addressed these questions by examining pilot interaction with the current generation of flight deck automation. Previous results on pilot-automation interaction derived from pilot surveys, incident reports, and training observations have produced a corpus of features and contexts in which human-machine coordination is likely to break down (e.g., automation surprises). We used these data to design a simulated flight scenario that contained a variety of probes designed to reveal pilots' mental model of one major component of flight deck automation: the Flight Management System.
(FMS). The events within the scenario were also designed to probe pilots' ability to apply their knowledge and understanding in specific flight contexts and to examine their ability to track the status and behavior of the automated system (mode awareness). Although pilots were able to "make the system work" in standard situations, the results reveal a variety of latent problems in pilot–FMS interaction that can affect pilot performance in nonnormal time critical situations.

The introduction of advanced technology to modern flight decks has succeeded in increasing the precision and efficiency of flight operations. However, recent accidents and incidents involving glass-cockpit aircraft have suggested that the current generation of cockpit automation may have created new operational burdens and new kinds of failure modes in the overall human–machine system (Billings, 1991). Only a limited empirical database is available concerning the nature and circumstances of existing problems in pilot–automation interaction (Eldredge, Dodd, & Mangold, 1991; James, McClumpha, Green, Wilson, & Belyavin, 1991; Wiener, 1989). These data consist primarily of either subjective data obtained from questionnaires and interviews or of in-flight observations of pilot interaction with one of the core systems of cockpit automation, the Flight Management System (FMS). The resulting data about pilots' attitude towards the system and the anecdotal reports of problems indicate that there is a need for further research that will systematically analyze the nature of and the reasons for FMS-related problems. This knowledge will be critical for developing countermeasures and improving pilot–automation interaction.

With this goal in mind, we studied pilot–FMS interaction through three different methodological approaches that allowed us systematically to collect converging data to describe existing problems and to understand why they exist. In the first report on our work (Sarter & Woods, 1992b), two exploratory research activities were described. A survey of pilots' self-reports of their operational experiences with the FMS and observations of transition training from a conventional to a glass-cockpit aircraft were used to gather a corpus of problems with FMS operation. This corpus consisted of detailed incident descriptions, from which major underlying problem categories were extracted.

These categories provided the basis for the design of a scenario for an experimental study of pilots' mental models and their awareness of the FMS. In this study, we confronted 20 experienced pilots with situations and tasks that are instances of the previously identified FMS-related problem categories. The pilots flew the scenario on a part-task training simulator that had been developed to teach FMS operations. As a result, it was possible to test the completeness and accuracy of their FMS-related knowledge as well as their ability to apply this knowledge in specific situations.
INTRODUCTION TO THE FMS

The FMS supports pilots in a variety of tasks, such as flight planning, navigation (guidance), performance management, and monitoring of flight progress. One of its major functions—and the function of primary interest in the context of the reported studies—is automatic flight-path control.

The major FMS controls in the cockpit are the mode control panel (MCP) and the multifunction keyboards of two control display units (CDUs; one for each pilot). FMS-related cockpit displays are the CDU multifunction display, two attitude director indicators (ADIs), and two horizontal-situation indicators (HSIs). Figure 1 illustrates the typical location of these different FMS components in a generalized glass cockpit.

The CDUs consist of a multifunction control unit (a keyboard) and a data display. The keyboard is used by pilots to enter data that define a flight path and to access flight-related data available on various pages within the CDU’s page architecture. The pilot-entered flight path, continuously updated to reflect current flight status, is presented on the map display of the HSI. This allows pilots to monitor progress along the path. In the HSI Plan mode, the pilot can visually check modifications to the active flight plan.

The MCP is used to activate different automatic flight modes: Vertical
Navigation (VNAV), Lateral Navigation (LNAV), Heading Select (HDG SEL), and Level Change (LVL CHG). The pilot can also use knobs on the MCP to dial in targets for individual flight parameters (airspeed, heading, altitude, and vertical speed), which are tracked by the system if a corresponding automatic flight mode is activated. To find out which FMS modes are currently active, the pilot can monitor the flight mode annunciations on the ADI. These provide data on the active (or armed) pitch and roll modes and on the status of the autopilot(s). They also indicate the status and mode of the autothrottles, which can be set to manual or automatic mode for speed and altitude control. The various FMS interfaces and autoflight functions provide the pilot with a high degree of flexibility in selecting and combining levels of automation to respond to different situations and requirements.

It is important to remember that there are various modes of automatic flight control that range between the extremes of automatic and manual. The highest level of automatic control occurs in the VNAV and LNAV modes. In these modes of control, the pilots enter—or, in their words, “program”—a sequence of targets into the CDU that defines an intended flight path, and then activate the automatics by selecting VNAV and/or LNAV through controls on the MCP. The Flight Management Computer automatically controls the aircraft to follow the desired flight path. At this strategic level of automation, the FMS pursues a sequence of target values without the need for further intervention by the pilot. This is particularly helpful in situations that allow for long-term planning with a low likelihood of deviations from the plan (e.g., in the cruise phase of flight).

When pilots need to intervene quickly and change flight parameters (e.g., in terminal areas), other lower levels of automation are available. Pilots can enter target values for different flight-path parameters (i.e., airspeed, heading, altitude, vertical speed) on the MCP. They can then activate one of the corresponding modes (e.g., Heading Select or Level Change), and the target will be captured and maintained automatically until the target or mode of control is actively changed by the pilot.

An important characteristic of automatic flight-path control is the high degree of dynamism. Transitions between modes of control occur in response to pilot input and to changes in flight status. Automatic mode changes can occur automatically when a target value is reached (e.g., when leveling off at a target altitude) or based on protection limits (e.g., to prevent or correct pilot input that puts the aircraft into an unsafe configuration).

Both the flexibility of the FMS and the dynamism of flight-path control impose cognitive demands on pilots. They have to decide which level and mode of automatic control to use in a given set of circumstances, and they also have to track the status and behavior of the automation. The latter task requires that they attend to and integrate data from a variety of indications in the cockpit such as flight mode annunciations on the ADI, visualization of the programmed route of flight on the HSI, or the display of target values on the MCP.
General Approach

The study was designed based on a phenomenon-driven ethnographic approach to studying cognitive systems in high-tempo event-driven worlds (Woods, 1993a). First, we had to identify an experimental environment for studying pilot–FMS interaction. It seemed important to account for the numerous concurrent tasks that have to be carried out by the pilot in the real operational environment and that could affect his or her FMS-related performance. Also, the impact of the high-tempo nature of flight had to be captured to arrive at valid results. Therefore, a strict laboratory study with a restricted set of tools and environmental fidelity was rejected. The other extreme on the scale of possible approaches—a high-fidelity full-mission simulation study—was rejected because some of its inherent capabilities (e.g., aircraft motion, outside view) were not essential to the purpose of this study and because there were high costs associated with obtaining access to such facilities. As a result, we chose an environment that allowed for realistic tools and tasks as well as for a fairly high level of fidelity: a part-task training simulator for FMS operations.

The next important step in conceptualizing the study was designing the scenario based on predefined phenomena of interest (Woods & Sarter, in press). This is much more than making the scenario as realistic as possible. A realistic setting only provides the background against which the scenario needs to be staged. In this study, the problem categories identified by our survey and by the training observations represented the phenomena of interest. The scenario-design process involved identification of specific tasks and events to be linked together in a coherent scenario that would probe these phenomena. This approach enables the experimenter to trigger behavior of interest rather than hoping for it to happen accidentally. Although this approach may underlie many simulation studies, it is often not explicitly laid out for the reader of a research article. In contrast, this article will provide a detailed description of the match between phenomena of interest and events within the simulated scenario.

Based on the scenario, a canonical model of pilot behavior in response to scenario probes and events was built (for the general case, see Woods, 1993a; for a different, specific example, see Roth, Bennett, & Woods, 1987). In contrast to normative models, which prescribe one acceptable response to each task or event, this canonical model describes a set of plausible trajectories—that is, it describes various possible ways in which pilots may behave in response to the scenario probes. This model was used to develop a data-recording instrument to encode observed pilot behavior directly during each test run.

An observer knowledgeable in FMS operations and the test scenario kept track of pilots’ interaction with the FMS on line by placing checkmarks
or—in the case of unanticipated behavior or events—comments on the data-collection sheet. In addition, pilots were asked to describe their reactions to hypothetical events that could not actually be simulated due to time restrictions and about FMS-related knowledge in general. These questions were asked in low-workload phases of flight without interrupting the simulation. This allowed us to probe pilots' knowledge within the actual operational environment instead of questioning them out of context, when their task would be more related to the retrieval of information than to its application. A few questions were asked before or after completion of the flight as they related to more general topics or to preflight activities.

After each test run, the instructor and the observer walked through the pilot's behavior and verbal responses during the simulated flight. This de-briefing helped elicit the instructor's interpretation of any ambiguous or unanticipated observations and helped prompt the instructor to add other observations that might have been missed.

The data were deliberately collected during the experiment rather than extracted after the fact from video and audio recordings of the simulation runs. Such recordings can be helpful for exploratory studies or in cases where a knowledgeable observer is not available. But even though retrospective analysis of videotapes may sometimes reveal unexpected or previously unattended but interesting behavior, there are disadvantages as well (e.g., investigators can be overwhelmed by the amount of data and thus be unsure of how to abstract broader results from all the details). It is more difficult to get line pilots and their representatives to agree to participate in a study when videotaping is involved. In addition, videotape is no substitute for careful and detailed identification of what one is looking for, based either on the mapping between phenomena of interest and the specific scenario or on what one might expect as canonical behavior for knowledge of that field of practice (Woods, 1993a; Woods & Sarter, in press).

Experimental Scenario

The experimental scenario for this study was designed to address predefined phenomena of interest. These phenomena had been identified by the corpus gathering activities (pilot survey and training observations) preceding the study (see Sarter & Woods, 1992b). The issues were related to (a) pilots' proficiency in standard tasks, (b) pilots' mental model of the functional structure of the FMS and (c) their awareness of system state and behavior (mode awareness). In cooperation with a flight instructor, we identified tasks and events that would best serve to probe these phenomena. The basic flight context consisted of a flight from Los Angeles to San Francisco that took approximately 60 min to complete.¹

¹The actual flight time is longer, but temporary increases in the simulated aircraft speed were used during quiescent phases of flight to reduce time on the simulator.
The following sections provide an overview of the mapping between phenomena of interest and specific tasks and events within the scenario. Figure 2 illustrates the flight route and the timing of the tasks and events throughout the scenario. To better understand the following description of the scenario, it might be helpful for the reader who is not familiar with glass-cockpit technology to review the Introduction to the FMS section of this article.

**Figure 2** The timing of scenario tasks and events along the flight route.
Proficiency in Standard Tasks

Table 1 lists the standard tasks that pilots carried out in the course of the scenario. Our previous study (Sarter and Woods, 1992b) showed that pilots' proficiency at standard tasks did not seem to be a major source of difficulties. It was included as part of this scenario to provide additional converging evidence based on a scenario evolving in real time and involving pilots with line experience in glass cockpits to confirm the previous results.²

Pilots' Knowledge of the Functional Structure of the FMS

By functional structure of the FMS we refer to pilots' knowledge about how the FMS behaves in different flight situations rather than their ability to simply recite facts about the FMS. For example, do they understand the sequence of mode changes, their associated indications, and the corresponding aircraft behavior throughout the takeoff roll?

To probe this phenomenon of interest, we built into the scenario a variety of tasks and situations that permitted inferences about pilots' knowledge of the system and their ability to apply this knowledge in actual task contexts. Knowledge of overall FMS functionality was subdivided into six subtopics (discussed hereafter), and specific probes were developed for each subtopic.

Knowledge of the CDU page architecture. The page architecture of the FMS CDU contains a huge amount of data that may be relevant at some point during the flight. Because only a very limited set of data can be presented on the CDU screen at any given time, pilots need to be able to navigate through the "hidden" data space. To find out about problems related to this task, pilots were asked to locate information on CDU pages on the following topics: (a) single-engine capabilities, (b) wind data for fixes of flight, (c) available fuel, and (d) localizer frequency and front course for a runway.

We also asked pilots about their expectations concerning data propagation throughout the CDU page architecture. After pilots had entered speed and altitude target values on the cruise page to comply with an amended clearance by ATC, we asked whether they expected these data to propagate to the descent page to become the targets for their descent.

²The group of standard tasks presented in this experiment did not include the Flight Management Computer System Performance Initialization, as we had already seen during the training observations that these tasks did not challenge the pilots. Also, we wanted to focus on tasks that have to be performed in the dynamic airborne portion of flight rather than on ground tasks that are not as affected by time pressure or concurrent tasks.
TABLE 1
Scenario Probes of Pilots' Proficiency at Standard FMS-Related Tasks

<table>
<thead>
<tr>
<th>Route changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercepting a radial</td>
</tr>
<tr>
<td>Going directly to a waypoint</td>
</tr>
<tr>
<td>Building and executing a hold</td>
</tr>
<tr>
<td>Installing an instrument-landing-system approach</td>
</tr>
<tr>
<td>Entering crossing restrictions</td>
</tr>
<tr>
<td>Unplanned level-off</td>
</tr>
<tr>
<td>Extending the final-approach fix</td>
</tr>
</tbody>
</table>

These probes were intended to test pilots' knowledge of the page architecture of the CDU as well as their ability to use the CDU interface to call up information and/or pages.

Mode availability and disengagement. After being vectored off-course by ATC, pilots were asked to recapture the preprogrammed route. This task was introduced to find out whether pilots were aware of the criteria that have to be met in order for the LNAV mode to capture the original flight path.

When being cleared by ATC for the instrument-landing-system approach, pilots were asked to set up the FMS properly to be able to use the automatic APPROACH mode. They had to remember that a lower MCP altitude had to be selected before engaging the APPROACH mode. Without this first step, the APPROACH mode engagement would not result in the desired start of descent; rather, the FMS would control the aircraft to maintain the MCP target altitude.

After localizer and glideslope capture on final descent, pilots were asked to describe how they would disengage the APPROACH mode if ATC told them to change heading and altitude for traffic.

These probes allowed us to determine whether pilots were familiar with the general prerequisites and procedures for engaging or disengaging a mode and whether they could apply this knowledge to a specific flight context.

FMC logic. After takeoff from Los Angeles, pilots were asked to intercept the LAX 249° radial outbound. To perform this task successfully using LNAV, the pilot had to understand that the FMS logic is to always fly towards—not away from—a waypoint. As his original flight plan did not include any waypoint on the radial, he first had to create a fictitious fix somewhere on the radial to which the FMS could fly.

After completion of the flight, we asked pilots about functional characteristics of the VNAV path descent in comparison to the VNAV speed descent. The questions referred to the way in which either one of these types of
descent is initialized, what control mode the system uses to maintain target speed in either mode, and what is the lowest altitude to which the system automatically descends.

**Effects of partial system failures.** During a descent, pilots were asked about the expected consequences of losing the autothrottles: Would the aircraft still level off at target altitude, and what would be the consequences in terms of airspeed? How would they intervene in that case?

After glideslope capture, we disabled the glideslope to simulate a signal loss at about 3,000 ft. This allowed us to test whether pilots would realize what happened, whether they would understand the implications of losing the glideslope, and how they would react to the failure. In addition, they were asked about the differences between a glideslope failure above versus below 1,500 ft above ground level (AGL).

If the glideslope signal is lost above 1,500 ft, the glideslope indicator (G/S) and the flight director bars disappear from the ADI, and the aircraft continues its descent at the current rate of descent. A flag indicating unreliable glideslope input appears only on the standby attitude indicator. Glideslope loss below 1,500 ft (where automatic system tests are conducted) results in both autopilots disengaging and in changes in the mode indications ("FLARE armed" is not annunciated).

**Protections.** While climbing to 5,000 ft with VNAV engaged, pilots were asked what other modes they could use for the climb. With respect to one of the possibilities—the Vertical Speed mode—they also were asked what happens when an excessive rate of climb is used (the FMS automatically reverts to the LVL CHG mode to maintain a safe airspeed).

**Various options for carrying out a task.** Pilots were asked to comply with ATC clearances by using the FMS the same way as in real line operations. Once they had decided to use a certain mode for a given task, they were asked about other possible ways of achieving the same goal. This provided us with information on their knowledge about options provided by the FMS as well as about their criteria for selecting modes under different circumstances.

Table 2 summarizes the probes built into the scenario to elicit pilots' understanding of the functional structure of the FMS.

**Mode Awareness.**

This section describes the probes that were built into the scenario for testing pilots' mode awareness. They help to determine whether pilots know what person or system is in charge of controlling the aircraft, what the
active target values are, and whether they can anticipate the status and behavior of the FMS.

*Who is in charge?* Immediately before takeoff, pilots were asked how they would abort the takeoff if necessary at approximately 40 kts with the autothrottles turned on. To cope adequately with the situation, pilots had to understand what regime the autothrottles follow during takeoff. As shown in Figure 3, the autothrottles will automatically go to N1 (a critical engine parameter) until indicated airspeed reaches 64 kts. At and above 64 kts, pilots can manually override the autothrottles. Thus, if takeoff is aborted before 64 kts, the autothrottles must be manually disengaged to prevent them from advancing again to reach N1.

Pilots' awareness of active mode settings was also probed by checking whether they (re)activated a corresponding mode after modifying target data in order to make the system work on reaching a new target state.

**TABLE 2**

Scenario Probes of Pilots' Knowledge of the Functional Structure of the FMS

<table>
<thead>
<tr>
<th>Locating data in the CDU page architecture</th>
<th>Tracking data propagation in the CDU</th>
<th>Applying knowledge about mode-capture criteria</th>
<th>Disengaging the automatic APPROACH mode after capturing localizer and glideslope</th>
<th>Intercepting a radial outbound</th>
<th>Questions concerning VNAV Speed mode versus VNAV Path descent mode</th>
<th>Loss of autothrottles during a descent</th>
<th>Loss of glideslope signal</th>
<th>Predicting effects of excessive rate of climb in V/S mode</th>
<th>Describing the different possible ways of doing a task</th>
</tr>
</thead>
</table>

![Figure 3](image-url) Autothrottle status, behavior, and indications throughout the takeoff roll.
What are the active target values? Several probes were used to find out about pilots' awareness of the current FMS target values. Shortly before takeoff, they were given an amended takeoff clearance involving a tailwind component. This required them to remember to change their N1 setting from reduced to full takeoff thrust.

During the cockpit setup, a pointer to the pilot-calculated N1 target value can be manually positioned on the forward engine display for reference purposes. However, if the autothrottles are active during takeoff, as in this scenario, they use the FMS-calculated N1 target, which is shown on the CDU takeoff reference page. To probe pilots' awareness of the relevant N1 value, the instructor manually positioned the N1 pointer on the engine display to a different value than the one indicated on the CDU. Pilots were asked which of the two values would be the target for the autothrottles during takeoff.

During an intermediate climb, the pilot-not-flying (PNF) activated the Control Wheel Steering (CWS) pitch mode by pulling on the yoke, thus overriding the active LVL CHG mode. The CWS pitch mode maintains the vertical rate that corresponds to the pilot-induced yoke position. The pilot-flying (PF) had to determine whether the aircraft would still level off at the target altitude that had been preselected on the MCP for the LVL CHG mode.

Anticipation of system status and behavior. Whenever transitions in aircraft behavior were imminent (e.g., level-off at a target altitude), the participants were asked what flight mode annunciations they expected to see on the ADI throughout the transition.

Table 3 summarizes the probes built into the scenario to test pilots' mode awareness.

Study Participants

The participants in this study were 20 airline pilots who responded to postings or who were approached by the airline's training department. Participation was voluntary, and pilots were paid a nominal compensation for their cooperation. The participating pilots either had a considerable amount of line experience on the B-737-300 (n = 14), or were about to finish their fixed-base transition training to the B-737-300 (n = 6). Table 4 describes their biographical data and flight background.

Procedure

Pilots were asked to fly individually a 60-min scenario on a B-737-300 part-task trainer. This simulator is equipped with all relevant cockpit instruments (including a fully functional FMS with the Electronic Flight Instrument System, communication and navigation radios, and engine displays). It
TABLE 3
ScenArio Probes of Pilots’ FMS-Mode Awareness

Aborted takeoff under 64 kts
Frequent changes in clearances involving mode transitions
Tailwind in takeoff clearance
Incorrect manual N1 setting
Activation of Control Wheel Steering during climb
Ask for predictions of ADI-mode indications

TABLE 4
Age and Flight Backgrounds of Pilots

<table>
<thead>
<tr>
<th>Variable</th>
<th>Experienced</th>
<th>Transitioning</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>Age (years)</td>
<td>41.1</td>
<td>10.1</td>
</tr>
<tr>
<td>Total flying time (hr)</td>
<td>8,471</td>
<td>4,539</td>
</tr>
<tr>
<td>Glass-cockpit experience (hr)</td>
<td>1,011</td>
<td>582</td>
</tr>
</tbody>
</table>


is based on an actual aircraft database, and it allows for any line-oriented operation except hand-flying the aircraft below 1,000 ft AGL. The major differences as compared to a full-mission simulator are that it does not generate a simulated out-the-window view or provide motion cues. However, these capabilities were not relevant to the topics investigated in this study. The simulator does not include any Traffic Alert and Collision Avoidance System equipment.

On arriving at the simulator, pilots were provided with the necessary paperwork (e.g., charts, approach plates, weather, weight manifest) as well as the LAX-ATIS and their clearance. The participants were asked to take their seat in the cockpit, and to act as PF during the flight. They were given as much time as they needed to familiarize themselves with the cockpit setup and the intended flight. The instructor told them that weather was not a consideration, no NOTAMs existed for the flight, and all appropriate checklists would be completed during the flight.

The instructor took care of the cockpit setup for the participant. He occupied the empty seat and acted as PNF and ATC throughout the flight. An observer was seated behind both pilots to collect behavioral and verbal data throughout the test run and to introduce scenario events through manipulation of the simulator (e.g., introduction of failures).

With respect to FMS-related tasks, each pilot was given these instructions:

1. All FMS-related work has to be done by the PF (the participant) after activation of the autopilot at 1,000 ft AGL.
2. Altitude changes on the MCP will be taken care of by the PNF [the instructor] as in actual line operations and the PF can command the PNF to carry out specified MCP manipulations for him.

3. All tasks should be carried out by the participant the same way as in real line operations.

4. Don't be in a hurry on the CDU or MCP! We want to keep track of what you are doing. Speed is not important for our purposes.

At various points during the scenario, pilots were asked to perform or describe FMS-related tasks, or were asked questions concerning their FMS-related knowledge. After completion of the flight, additional questions were asked concerning FMS logic and operations, and the pilots were given the chance to ask the instructor about tasks and events that occurred during the test run.

RESULTS

The data were first analyzed across all of the participants to identify tasks and events that posed problems to the majority of pilots. Subsequently, pilots' behavior and misconceptions with respect to these probes were looked at in greater detail. A dedicated section deals with any significant differences between the performance of pilots with glass-cockpit line experience versus those without such experience. No other differences were apparent for any other pilot factors such as pilot's seat or age. For some tasks that allowed pilots to choose among several different approaches, the preferred strategies for the two pilot groups are presented. Finally, problems related to mode activation that occurred across different tasks are examined more closely.

Problematic Tasks and Events

Fewer than 6 pilots (30%) had any difficulties carrying out the routine tasks of changing a route (i.e., creating/entering new waypoints/airways), intercepting a radial, building or executing a holding pattern, installing an instrument-landing-system approach, and entering crossing restrictions for waypoints along the route.

On the contrary, more than 14 pilots (70%) showed deficiencies in (a) aborting a takeoff at 40 kts with autothrottles on, (b) anticipating ADI mode indications throughout takeoff roll, (c) anticipating when go-around mode becomes armed throughout landing, (d) disengaging Approach (APPR) mode after LOC and G/S capture, (e) explaining speed management, (f) defining end-of-descent point for VNAV path versus VNAV speed descent, and (g) describing the consequences of G/S loss above and below 1,500 ft.
The first three of these tasks are related to mode awareness either in the context of dealing with an FMS-related failure or in the sense of anticipating system status and behavior. The last four tasks point out deficiencies in pilots' knowledge of the functional structure of the system. The results revealed in detail the kinds of problems that can arise in pilot-automation interaction and the misconceptions that pilots can have about the FMS.

**Aborted takeoff.** Immediately before receiving their takeoff clearance, pilots were asked what procedure they would use to abort the takeoff at 40 kts. Although it was emphasized that the takeoff had to be aborted at 40 kts—before Throttle Hold (THR HOLD) is reached at 64 kts, when the pilot can manually position the throttles—16 pilots (80%) described the procedure as “Throttles back, reversers, and manual brakes.” They did not mention that the autothrottles would have to be disconnected to prevent the throttles from coming back up again after manual intervention. When explicitly asked whether they would also disconnect the autothrottles, three participants (15%) realized that they had missed that item. Three pilots (10%) were not sure about this question and suggested that they would hold the A/Ts back manually, “just in case.”

Only four pilots (20%) responded by immediately disconnecting the autothrottles to abort the takeoff. They were asked why this action is necessary, and all but one pilot properly described the reason. This pilot explained that he would disconnect the autothrottles because he thought that this was standard procedure, but he indicated that he was not aware of the consequences of failing to carry out this step.

**Anticipation of ADI indications during takeoff.** Pilots were asked for their expectations concerning ADI mode indications throughout the takeoff roll, as these indications are supposed to help monitor whether the system is working properly and as expected.

The relevant indications that appear in the lower left corner of the ADI are N1—that the autothrottles are in charge and will go to takeoff thrust—and THR HOLD—that the aircraft has reached 64 kn and the autothrottles will go to takeoff thrust but that they can now be overridden manually by the pilot. Five of the pilots (25%) expected to see both these indications. Twelve subjects (60%) only mentioned either THR HOLD (15% of the pilots) or N1 (45% of the pilots) as an indication during takeoff. Another 3 pilots (15%) could not predict any of the mode indications.

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3In the debriefing, these pilots argued that they could still hold the throttles back manually to prevent them from advancing without disengaging them. But it is not clear that they would do so in the actual situation because, without understanding FMS behavior, it seems unlikely that they would anticipate the need for manual intervention.
Availability of GA mode. The GA mode becomes available when descending below 2,000 ft radio altitude with the autothrottles armed. Out of 20 pilots, only 5 recalled the altitude at which this occurs. Eight pilots (40%) knew that the availability of the mode depends upon reaching a certain altitude, but they did not remember the actual height. Another 4 pilots (20%) replied that they had no idea when the mode becomes available, and the remaining 3 pilots (15%) assumed that the GA mode is available upon glideslope capture.

Disengaging the APPR mode after LOC and G/S capture. When asked to disengage the APPR mode after localizer and glideslope had been captured, only 3 pilots (15%) could recall the three ways of accomplishing this (pushing the Takeoff/Go-Around buttons on the throttles, turning both flight displays and the autopilot off, or retuning the VHF radio). Seven pilots (35%) did not know of any procedure for disengaging the APPR mode. Three pilots (15%) were familiar with two of the three different options.

The solutions suggested by the remaining 7 pilots (35%) included at least one possible approach, but also at least one approach that would not result in the disengagement of the APPR mode:

1. Six pilots (30%) thought that they could disengage the APPR mode by pushing the APPR key again.
2. Five pilots (25%) expected that engaging another pitch mode, such as V/S or ALT HOLD, would get them out of the APPR mode.
3. Five pilots (25%) thought that they would have to disengage either the A/P or the FDs, but not both.
4. Four pilots (20%) assumed that choosing another roll mode would solve the problem (e.g., Heading Select or VORLOC).

One interesting characteristic of these different unsuccessful attempts to disengage the APPR mode is that they seem to be intuitive approaches that are not supported by the system design.

Speed management and end-of-descent point in VNAV Path versus VNAV Speed mode. Knowledge of the control modes (pitch and power) used to maintain a target airspeed during a descent is important for pilots to be able to monitor and anticipate aircraft behavior. It allows them to recognize unexpected activities or the lack of timely aircraft response. Nine out of 20 pilots knew how the FMS maintains target speed during a VNAV Path descent. Eight pilots (40%) were aware of the speed control mode during a VNAV Speed descent. With respect to the end-of-descent point of a path descent versus a speed descent, the results were similar: Twelve pilots (60%) were aware of the end of descent during a
VNAV Path descent, and 9 pilots (45%) knew at what point the VNAV Speed descent would end.

Consequences of G/S failure above and below 1,500 ft. After G/S capture, a G/S signal loss was simulated at approximately 3,000 ft (before automatic system tests are carried out at 1,500 ft that can detect the absence of a valid G/S signal and automatically disconnect the autopilot). On realizing the problem, pilots were asked about the consequences of this event, and 54% of the pilots provided the correct answer. When asked whether a G/S failure at a lower altitude (<1,500 ft) would have different effects, only 15% of the pilots knew the answer. Twenty-three percent of the participants did not know the answer to either question.

Although detection time was not measured for this failure, it took some pilots a rather long time (several minutes in some cases) even to realize the problem even though they were looking directly at the ADI (with the G/S indications and FD bars disappearing) during this phase of flight.

Differences Between Line-Experienced and Transitioning Pilots

Major differences in performance between line-experienced and transitioning pilots were seen only with respect to three of the tasks within the scenario. First, when asked to intercept the LAX 248° radial, all 6 of the transitioning pilots had difficulties carrying out the task using LNAV, as compared to only 7 of the 14 experienced pilots. None of the inexperienced pilots realized the need for building a fictitious waypoint on the radial. Second, when asked about the consequences of using an excessive vertical rate of climb in the V/S mode, none of the transitioning pilots could provide the correct answer, as compared to only 5 (36%) of the experienced participants. Last, 5 of the 6 pilots without line experience could not describe how to program an intermediate descent on the VNAV Cruise page for avoiding traffic, whereas none of the 14 experienced pilots had any problem with this task.

Preferred Strategies of FMS Usage

In addition to probes that allowed for only one correct answer or reaction, some situations were built into the scenario that required pilots to choose among different options to carry out the task. We asked pilots to use the automation as they would in real line operations. This provided us with behavioral data on their primary choice of modes for a given task under specified circumstances. Subsequently, we asked them about other possible strategies for achieving the same objective.
Intercepting a radial outbound without a waypoint at a low altitude. There are two possible methods for accomplishing this task. First, pilots can use the VOR/Localizer mode (VORLOC), which involves MCP manipulations, or they can use LNAV, which requires working with the CDU. As Figure 4 illustrates, most of the pilots with glass-cockpit experience preferred to use VORLOC (93%), whereas the pilots in transition to glass cockpits preferred to use LNAV (83%).\textsuperscript{4} Although it is possible to use LNAV for this task after one creates a fictitious fix outbound, the MCP VORLOC mode is the faster and easier method at low altitudes; it requires less pilot input and no heads-down time as compared to creating a fix using the CDU.

Speed-restricted climb to 5,000 ft. Again, there are two options available to pilots: using the LVL CHG mode via MCP manipulations or modifying data on the CDU climb page and activating the VNAV mode. In this case, all of the pilots in transition and 79% of the experienced glass-cockpit pilots preferred the LVL CHG mode of the MCP (see Figure 5). Again, using the MCP minimizes heads-down time, which is important as the aircraft is still at a very low altitude during this task.

Unplanned descent for traffic at FL 290. In this situation, the pilots could either choose the LVL CHG mode on the MCP or they could program the descent on the CRZ page of the CDU and then activate VNAV. As Figure 6 shows, the majority of line-experienced pilots chose to descend using VNAV (79%), whereas most (83%) of the less experienced pilots preferred to use the LVL CHG mode. When asked why they preferred VNAV, the experienced pilots explained that, because they were at FL 290, they felt they had enough time to program the CDU. They also said that they would prefer to modify the VNAV data right away rather than switch between VNAV and another descent mode at a lower level of automation, which makes it more difficult for them to keep track of active modes and targets.

Problems of Mode Activation

Another interesting result refers to failures to engage or reengage a mode after entering new target values into the MCP or the CDU. This omission occurred at least once during the scenario for 5 of the 6 transitioning pilots (total number of omissions = 9). Only 2 of the 14 experienced pilots forgot to engage an appropriate mode, and this occurred only once for each of

\textsuperscript{4}Some of the pilots in transition (16%) could not think of any second method at all.
First Choice

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<th>Transitioning Pilots (n = 6)</th>
<th>Experienced Pilots (n = 14)</th>
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<tbody>
<tr>
<td><strong>LNAV (CDU)</strong></td>
<td>83</td>
<td>7</td>
</tr>
<tr>
<td><strong>VORLOC (MCP)</strong></td>
<td>93</td>
<td>17</td>
</tr>
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FIGURE 4 Preferred mode and level of automation for intercepting a radial outbound for experienced versus transitioning pilots.

First Choice

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<th>Transitioning Pilots (n = 6)</th>
<th>Experienced Pilots (n = 14)</th>
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</thead>
<tbody>
<tr>
<td><strong>VNAV (CDU)</strong></td>
<td>0</td>
<td>21</td>
</tr>
<tr>
<td><strong>LVL CHG (MCP)</strong></td>
<td>100</td>
<td>79</td>
</tr>
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FIGURE 5 Preferred mode and level of automation for a speed-restricted climb at low altitude for experienced and transitioning pilots.
FIGURE 6  Preferred mode and level of automation for an unplanned descent for traffic at high altitude for experienced and transitioning pilots.

them. The problem occurred 4 times with LNAV mode, 6 times with VNAV mode, and 1 time with LVL CHG mode.

In 7 of the failures to engage a mode, all required entries into the CDU or the MCP were made, but no mode was activated. In the remaining 4 instances, the pilot would first use an MCP mode (e.g., HDG SEL) to get the system started towards the target, and then he would enter the new target data into the CDU, but ultimately he would forget to switch from the MCP mode to VNAV or LNAV, which use the entered CDU values as targets. The fact that pilots forgot to engage VNAV or LNAV (rather than an MCP mode) after entering new target data in the majority of cases may be related to the spatial separation between the data-entry unit (CDU) and the VNAV and LNAV buttons on the MCP. It can also be interpreted as an indication of a flawed mental model of the FMS, in which the close relation between the CDU (target-entry unit) and the MCP (mode-activation unit) is not well represented.

Another problem related to mode engagement was the attempt to activate a mode without the prerequisites for this activation being met. Fifty percent of the transitioning pilots and 1 of the 14 experienced pilots tried to engage VORLOC without being in the manual radio mode as required. Fifty percent of the transitioning pilots and 5 of the 14 experienced pilots engaged the APPROACH mode without lowering the MCP altitude first, and they were surprised to find that the aircraft did not start the descent.
This study supports and expands on the results obtained from the previous corpus gathering studies of pilot–automation interaction (Sarter & Woods, 1992b). It confirms that most of the difficulties in pilot–automation interaction are related to a lack of mode awareness and to gaps in pilots’ mental models of the functional structure of the automation. These problems seem to occur primarily in the context of nonnormal time-critical situations such as an aborted takeoff. Problems related to such situations may be underreported in surveys because they rarely occur in line operations. In this study, however, every participant was forced to cope with nonnormal events in the scenario. In this way, latent problems in pilot–FMS interaction could be revealed.

For the majority of pilots, it was difficult or impossible to manage the cockpit automation in three nonnormal time-critical situations in the scenario: (a) an aborted takeoff, (b) the need to disengage an automatic approach mode for collision avoidance, and (c) loss of the G/S during final descent. In the case of the aborted takeoff, 65% of all participants did not understand how the autothrottle controls the aircraft throughout the takeoff. Fifteen percent of the pilots knew about the ongoing mode activities and transitions, but they were not capable of applying this knowledge to the situation at hand. In terms of behavior, this resulted in only four pilots responding correctly, and one of them did not seem to understand completely the basis for this action. With respect to the request to disengage the APPROACH mode after localizer and glideslope capture, most of the pilots knew at least one way of complying with this request. However, 14 pilots also suggested at least one ineffective approach. If, in a real world case, ATC told the pilot to change heading and/or altitude immediately to avoid a collision, there would be no time for failed attempts to disengage the mode; the pilot would have to respond immediately. This problem is related to the need for an interface design that can indicate available options to help the pilot intervene quickly and directly when necessary. In the case of the loss of the G/S during final descent, we observed that it took many pilots fairly long even to realize that an anomaly had occurred. Although they were looking directly at the ADI display at this stage of the simulated flight, it took some pilots several minutes to realize that the G/S indication and the FD bars had disappeared, both of which are the only ADI indications of the problem until the aircraft descends through 1,500 ft (when automatic system tests are conducted that can detect an invalid G/S signal, disconnect the autopilot, and issue alerts to the pilot). This problem illustrates that cueing by absence may not be a good technique for indicating the presence of an anomaly. Not only was anomaly detection relatively slow, but about half of the participants were not aware of the consequences of a loss of the G/S.

The scenario contained a variety of other probes of the pilots’ ability to be
“ahead of the FMS”—that is, to show the ability to anticipate future system behavior that can change not only in response to current pilot input, but also as a result of changes in the environment, previous pilot input, or for protection purposes (Reason, 1990). For example, only 1 out of 20 participants could predict the entire sequence of expected mode indications for the takeoff roll. Similarly, only 5 of the participants knew when to expect the indication that the go-around mode was available.

The underlying reason for the observed problems seems to be a lack of mode awareness. In the context of simpler devices and environments, mode awareness usually refers to the adequate assessment of the currently active mode status. But our results show that in the context of the highly dynamic and complex cockpit environment, other aspects of mode awareness are more critical. In these systems, the pilots' role has changed from active manipulator of the aircraft to supervisor of the automated systems. To fulfill this role, pilots need to have a thorough understanding of what a mode means in terms of system behavior and have to be “ahead of the FMS.”

Operational Costs of Technology-Centered Automation

New automation is developed because of some payback (e.g., precision, more data, reduced staffing, etc.) or for some beneficiary (e.g., the individual practitioner, the organization, the industry, or society). But often overlooked is the fact that new automated devices also create new demands for the individual and groups of practitioners responsible for operating and managing these systems. New demands can include new or changed tasks (e.g., setup, operating sequences) as well as new cognitive demands. There are new knowledge requirements (e.g., how the automation functions), communication tasks (e.g., instructing the automation in a particular case), data-management tasks (e.g., finding the relevant page within the CDU page architecture), attention demands (e.g., tracking the state of the automation), and forms of error or failure (e.g., mode error). This study reveals some of the kinds of costs that can occur in the context of the current generation of cockpit automation—costs that can be minimized or eliminated through skillful design of human-centered automation (Billings, 1991).

Mode error and mode awareness. Two of the cost centers associated with changes in automation are the possibility of new forms of error or failure and the possibility of creating new cognitive demands for practitioners. Interlinked examples of these effects of automation for the glass cockpit case are mode error and mode awareness.

Devices that allow something to be done one way in one mode and another way in another mode create the possibility of mode errors, in which
one executes an intention in a way appropriate to one mode when the device is actually in another mode (Norman, 1988). Automated systems like those in the glass cockpit cannot be characterized by a single mode setting. There are a number of subsystems, each involving a number of possible mode settings. This increase in the power and flexibility of automated resources creates a form of operational complexity that increases the potential for mode errors.

But advanced automation like the FMS extends the kinds of mode-related problems that can occur because system status and behavior can change independent of immediate and direct pilot commands due to situation factors or protection limits (Sarter & Woods, 1992a). This means that a new cognitive demand is created: the need to maintain awareness of externally induced mode transitions. As the pilot's role has changed from active manipulator of the aircraft to supervisor of automated systems, effective situation awareness requires pilots to stay ahead of the FMS—that is, to be able to anticipate future system behavior or to detect system failures (Sarter & Woods, 1991). However, in this study, only 5 out of 20 participants could predict the operationally most significant mode indications (N1 and THR HOLD) for the takeoff roll, and only 5 of the participants knew when to expect the indication that the go-around mode is available.

One way to interpret the results of this study and the complementary results of Sarter and Woods (1992b) is that many of the observed problems resulted from a lack of mode awareness—the pilots lost track of system targets and missed mode changes that occurred independently of immediate pilot commands. Maintaining mode awareness requires pilots to attend to and integrate data from a variety of indications in the cockpit such as the flight mode annunciations on the ADI, the visualization of the programmed route of flight on the HSI, and the display of target values on the MCP. Breakdowns in mode awareness may be due to characteristics of these indications, given the nature of the cognitive demands of high-tempo phases of flight or nonnormal flight situations. Another contributor to these attentional breakdowns may be limits and gaps in the pilots mental models of the automated resources.

**New knowledge requirements.** Transition to glass-cockpit aircraft requires pilots to learn a great deal about the FMS and other flight-deck automated subsystems. As the results of this study show, and given the results of the previous corpus building studies, there are a number of areas where pilots have gaps in their understanding of the functional structure of the FMS. By forcing pilots to deal with various nonnormal situations, gaps or errors in their understanding of how the automation works in various situations were revealed. Again, the results indicated that pilots do not have an accurate model of how VNAV descent modes work and that the displays do not help them in tracking either the targets or the control modes used by
VNAV Path and VNAV Speed descents. Overall, this study confirms previous results (Sarter & Woods, 1992b) and shows that these problems can occur even with pilots who have relatively extensive glass-cockpit experience.

Note the interaction between two factors. First, breakdowns in mode awareness can be due in part to a lack of effective feedback on the state of the automation and in part due to buggy mental models of the automation. Second, the lack of feedback on the state of the automation can limit pilots' ability to learn from experience, to correct or elaborate their mental models of system function over time, and to learn to perceive the state of the automation from the available indications. A third factor further complicates the difficulty: Many of the flight situations that stress these problems occur relatively rarely in line operations.

This combination has broad repercussions for training pilots to manage highly automated aircraft. First, training must go beyond simply providing pilots with facts about the FMS. The results show that sometimes pilots possessed knowledge in the sense of being able to recite facts, but that they were unable to apply the knowledge successfully in an actual flight context. This is called the problem of inert knowledge. Training must conditionalize knowledge to the contexts where it is utilized. Second, pilots need to learn not simply how the automated system works, but also how to work the system. This requires scenarios and instruction designed around managing the transitions between different modes of automation. Third, because pilots do learn a subset of methods to be able to make the system work under routine conditions, situations that challenge their current understanding may arise relatively infrequently (or go unnoticed as such due in part to lack of feedback about the state and behavior of the FMS). This means that ongoing learning programs will need to be devised that help even experienced glass-cockpit pilots discover and correct subtle bugs in their mental models of the FMS or to elaborate their understanding of how the automation works in particular situations in a risk-free environment.

Knowledge miscalibration. The results indicate that pilots have gaps in their understanding of the functional structure of the FMS. Further, there are some indications in the data that pilots are miscalibrated with respect to their understanding of the FMS—that is, pilots may not be aware of the gaps in their mental models. An expert is well-calibrated if he or she is aware of the areas and circumstances in which they have correct knowledge and in which their knowledge is incomplete or limited. If the expert is overconfident and believes that he or she understands areas in which their knowledge is in fact incomplete or limited, then that person is said to be miscalibrated (Wagenaar and Keren, 1986). Note that degree of calibration is not necessarily correlated with expertise.

When we compare pilot responses to questions like "How much do you
agree or disagree with the statement: ‘There are still modes and features of the FMS that I don’t understand’” (Sarter & Woods, 1992b; Wiener, 1989) to the behavioral data in this study, there is some indication that glass-cockpit pilots are overconfident and miscalibrated about how well they understand the FMS. When forced to cope with flight situations that challenge their ability to monitor and manage cockpit automation, the number and severity of pilots’ problems was higher than would be expected from previous survey data, in particular for pilots with line experience in glass cockpits. Some of the participants in this study made comments in the post-scenario debriefings such as: “I never knew that I did not know this. I just never thought about this situation.” Similar results have been obtained in studies of physician interaction with computer-based automated devices in the surgical operating room (Cook, Potter, Woods, & McDonald, 1991; Moll van Charante, Cook, Woods, Yue, & Howie, 1992)

There are several factors that could have contributed to the observed miscalibration. First, areas of incomplete or buggy knowledge could have remained hidden from pilots because they have the capability to work around these areas by sticking with a few well-practiced and well-understood methods. In addition, flight situations that force pilots into areas where their knowledge is limited and miscalibrated may arise infrequently. Second, studies of calibration have indicated that the availability of feedback, the form of feedback and the attentional demands of processing feedback can effect knowledge calibration (Wagenaar & Keren, 1986). Problems with ineffective feedback on the state and behavior of the FMS observed in this study and reported on in previous studies of pilot interaction with cockpit automation (e.g., Norman, 1990) could have been a factor that contributed to poor calibration of pilots—that is, a lack of awareness of the gaps in their mental models of the FMS. The relation between poor feedback and miscalibrated practitioners was also found in studies of physician–automation interaction (e.g., Cook et al., 1991). Knowledge miscalibration in pilots, if it is widespread, is one factor that could lead to underreporting of problems with cockpit automation in survey studies.

How to manage automated resources. Cockpit automation provides a large number of functions and options for carrying out a given flight task under different circumstances. For example, the FMS provides at least five different mechanisms at different levels of automation for changing altitude. This flexibility is normally construed as a benefit that allows the pilot to select the mode or option best suited to a particular flight situation (e.g., time and speed constraints). However, this flexibility creates new demands as well. Pilots must learn and know about the functions of the different modes, how to coordinate which mode to use when, and how to switch smoothly from one mode to another. In other words, the pilots must know how the automated system works and must develop skill at how to
work the system. To meet the latter criterion, pilots must: (a) learn about all of the available options; (b) learn and remember how to deploy them across a variety of operational circumstances, especially rarely occurring but more difficult or critical ones; (c) learn and remember the interface manipulations required to invoke the different modes or features; and (d) learn and remember how to interpret or where to find the various indications about which option is active or armed and what its associated target values are.

The results of this study indicate that pilots become proficient and maintain their proficiency on only a subset of the modes and options provided by the FMS. Further evidence for this phenomenon was provided by previous FMS-related studies (Sarter & Woods, 1992b) and by studies of human–machine interaction in other domains (e.g., Cook, Woods, & Howie, 1990; Rosson, 1983), where users hardly ever use more than a small subset of the options provided. This is, in part, a consequence of the increased costs involved in learning extra functions, but it also allows practitioners to protect themselves from having to make difficult decisions due to an increased number of alternatives. In the case of the FMS, pilots try to manage the system within a set of stereotypical responses or techniques. In this study, we were able to compare the tactics selected by pilots with line experience in glass cockpits with those selected by pilots without previous glass-cockpit experience. The results indicate that, over time, pilots learn to select among the various options depending on situation factors (e.g., altitude, time constraints) and on expectations (e.g., the likelihood of deviation from plan). But pilots who had just finished their transition training were much less sensitive to these contextual factors. They tended always to use the highest level of automation independent of context.

Note that, in higher tempo phases of flight, more experienced pilots in our study chose to use intermediate levels of automation that use the MCP as the interface rather than higher levels of automation that require CDU interaction. The MCP-based modes generally require less interaction, less head-down time, and less diversion of attention to the interface itself (e.g., remembering the necessary interface manipulations). In addition, the modes of automation accessed through the MCP as an interface tend to respond only to direct pilot input (e.g., the pilot enters a target value and activates a mode of control, and the automation then responds by capturing and maintaining that target value until another pilot command is received) and do not initiate a sequence of automated system activities. This may explain previous results in which pilots saw the MCP and the CDU as separate systems (Sarter & Woods, 1992b) despite the fact that, from an engineering point of view, both are part of an integrated FMS. Operationally, interacting with the MCP modes has a different character than programming the CDU. This means that general questions about pilots’ attitudes towards cockpit automation in general are ambiguous, and that pilots may differ from each other and from the investigator in their interpretation of what aspects of cockpit automation the question refers to.
SUMMARY

The results of this and previous studies of pilot interaction with cockpit automation in commercial aviation yield consistent results across diverse methods. Although pilots seem to be able to make the system work in standard situations, one of the most important results of this study is the discovery of latent problems with pilot–FMS interaction that can affect even experienced pilots’ performance in nonnormal time-critical situations. The severity and importance of these problems is underestimated due to several interacting factors:

1. There are gaps in pilots’ understanding of the functional structure of the automation.
2. The opaque interface between pilots and automation makes it difficult for pilots to track the state and activity of the automation.
3. Pilots may not be aware of the gaps in their knowledge about FMS function.
4. Pilots can escape from the CDU to the MCP whenever a situation gets too complicated or time pressure is too high.
5. The flight situations in which these problems produce unmistakable performance difficulties may occur infrequently in line observations.

The data in this study, in conjunction with the data from previous studies (e.g., Norman, 1990; Sarter & Woods, 1992b; Wiener, 1989), point out some of the costs of the “clumsy” use of technological possibilities from an operational point of view. These costs should provide input to designers trying to develop human-centered automation and to trainers trying to develop new instructional programs for developing, maintaining and testing pilot proficiency in managing automated resources. However, it is important to remember that the problems in pilot interaction with cockpit automation are not inherent in the technology itself; rather these problems result from limitations in how the automation and the human pilots are integrated together as a joint, distributed cognitive system through both training and design (Hutchins, 1991; Woods, 1993b).

ACKNOWLEDGMENTS

This work was supported under Cooperative Agreement NCC 2-592 with the Aerospace Human Factors Research Division of the NASA-Ames Research Center. Dr. Everett Palmer was the technical monitor.

The authors thank all of the pilots who participated in the study and shared their experience with us. We are also very grateful for the support and patience of a large number of people at the collaborating airline who made it possible to carry out this line of research.
REFERENCES


