Pilot Interaction with Cockpit Automation II: An Experimental Study of Pilots' Model and Awareness of the Flight Management System (FMS)

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ABSTRACT

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 to operators to regulators and researchers have begun to ask questions about how should we use the possibilities afforded by technology skillfully to support and expand human performance. In this paper we report on an experimental study that addresses these questions by examining pilot interaction with the current generation of flight deck automation. Previous results on pilot-automation interaction derived from pilot surveys, incidents reports and training observations that have produced a corpus of features and contexts where 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 models of one major component of flight deck automation, the Flight Management System (FMS). The events within the scenario also were 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). While 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 non-normal time critical situations.

INTRODUCTION

The introduction of advanced technology to modern flight decks has succeeded in terms of 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 data base is available concerning the nature and circumstances of existing problems in pilot-automation interaction (Wiener, 1989; Eldredge, Dodd and Mangold, 1991; James et al., 1991). 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 systematically analyzes the nature of and the reasons for FMS-related problems. These results will be critical in order to develop countermeasures and to improve pilot-automation interaction.

With this goal in mind, we studied pilot-FMS interaction through three different methodological approaches that allowed us to systematically collect converging data to describe existing problems and to understand why they exist. In the first report on our work (Sarter and Woods, in press), 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 the operation of the FMS. 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 model and their awareness of the FMS. In this study we confronted twenty 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 FLIGHT MANAGEMENT SYSTEM

The following section provides a brief, simplified overview of the Flight Management System (FMS). The FMS supports pilots in a variety of tasks such as flight planning, navigation, performance management, and flight progress monitoring. 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 (one for each pilot). FMS-related cockpit displays are the CDU multifunction display, two Attitude Director Indicators (ADI), and two Horizontal Situation Indicators (HSI). Figure 1 illustrates the typical location of these different FMS components within a generalized glass cockpit.

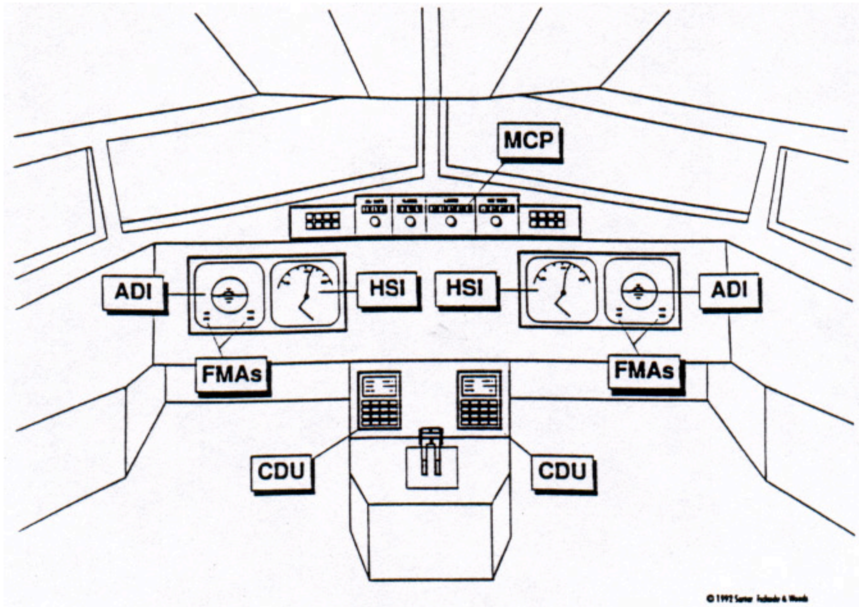

Figure 1. Flight deck controls and displays related to pilot-FMS interaction within a generalized glass cockpit

The Control Display Units (CDU) consist of a multifunction control unit (keyboard) and 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 page architecture. The pilot-entered flight path, continuously updated to reflect the current flight status, is presented on the map display of the Horizontal Situation Indicator (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 Mode Control Panel is used to activate different automatic flight modes (e.g. VNAV, LNAV, HDG SEL, 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 Attitude Director Indicator (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 terms of 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 (Vertical Navigation) and LNAV (Lateral Navigation) modes. In these modes of control, the pilots enter (or, in their words, "program") a sequence of targets that define an intended flight path into the CDU, and then activate the automatics by selecting VNAV (Vertical Navigation) and/or LNAV (Lateral Navigation) through controls on the Mode Control Panel (MCP). The Flight Management Computer (FMC) 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. cruise phase of flight).
When the pilot needs to quickly intervene and change flight parameters (e.g. in terminal areas), other lower levels of automation are available. The pilot can enter target values for different flight path parameters (i.e. airspeed, heading, altitude, vertical speed) on the Mode Control Panel (MCP). He then activates one of the corresponding modes (e.g. Heading Select or Level Change), and the target will be captured and maintained automatically until target or mode of control are 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 (i.e. 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 the pilot. He has to decide which level and mode of automatic control to use in a given set of circumstances, and he also has to track the status and behavior of the automation. This latter task requires that he attends to and integrates data from a variety of indications in the cockpit such as the Flight Mode Annunciations on the Attitude Director Indicator, the visualization of the programmed route of flight on the Horizontal Situation Indicator, or the display of target values on the Mode Control Panel.

METHODOLOGY

General Approach

The study was designed based on a phenomenon-driven ethnographic approach to studying cognitive systems in high-tempo event-driven worlds (Woods, in press). 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 may affect his 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, i.e. a high-fidelity full-mission simulation study, was not selected because some of its inherent capabilities (e.g. aircraft motion, outside view) were not essential for 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 allows for both 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 and Sarter, in press). This is much more than simply making the scenario as realistic as possible. A realistic setting only provides the background on which the scenario needs to be staged. In this study, the problem categories identified by our survey and the training observations represented the phenomena of interest. The scenario design process involved identification of specific tasks and events linked together in a coherent scenario that would probe these phenomena. This approach enables the experimenter to trigger behavior of interest rather than hope for * to happen accidentally. While this approach may underlie a large number of simulation studies, it is often not explicitly laid out for the reader of a research report. In contrast, this paper will provide a detailed description of the match between phenomena of interest and events within the simulated scenario.

The data collection included both verbal and behavioral reports. An observer knowledgeable about FMS operations and about the test scenario kept track of pilots' interaction with the FMS on-line by means of a data-collection sheet that laid out the possible trajectories of the scenario and pilot behavior. In addition, pilots were asked to describe their reactions to hypothetical events which 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 the flight without interrupting the simulation. This allowed us to probe pilots' knowledge within the actual operational environment rather than questioning them out of context where 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.

The data were collected throughout the experiment rather than extracted from video and audio recordings of the simulation runs after the fact. Such recordings can be helpful for exploratory studies or in cases where a knowledgeable observer is not available. But even though the retrospective analysis of videotapes may sometimes reveal unexpected or previously unattended but interesting behavior, there are disadvantages as well (e.g., investigators who are overwhelmed by the amount of data and unsure of how to abstract broader results from all the details). In this case getting actual line pilots to volunteer to participate in the study virtually ruled out the use of videotape (e.g., getting practitioners and their representatives, unions, to agree is prohibitively difficult). In addition, videotape is no substitute for careful and detailed identification of what one is looking for based on the mapping between phenomena of interest and the specific scenario; and videotape is no substitute for careful and detailed identification of what one might expect as canonical behavior based on knowledge of the field of practice (Woods, in press; Woods and 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 and Woods, in press). 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 which took approximately 60 minutes to complete[1].

The following paragraphs 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. In order to better understand the following description of the scenario, it may be helpful for the reader who is not familiar with glass-cockpit technology to take a look at the short introduction to the FMS that was provided in the first part of this paper.

[1] The actual flight time would be longer but temporary increases in the simulated aircraft speed were used during quiescent phases of flight to reduce time on the simulator.

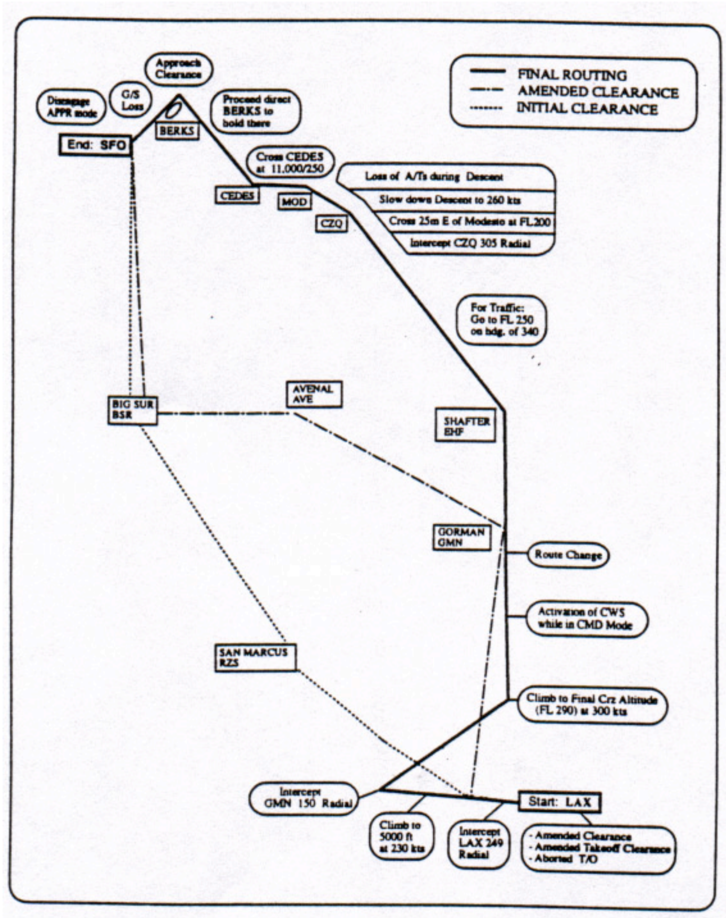

Figure 2. The Timing of Scenario Tasks and Events along the Flight Route

Proficiency in Standard Tasks

Table 1 lists the standard tasks that pilots had to carry out in the course of the scenario. The previous study (Sarter and Woods, in press) 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].

[2] The group of standard tasks presented in this experiment did not include the FMCS/Performance Initialization as we has already seen during the training observations that these tasks did not challenge the

Table 1. Scenario Probes of Pilots' Proficiency in Standard FMS-Related Tasks

- Route Changes
- Intercepting a Radial
- Going direct to a waypoint
- Building and Executing a Hold
- Installing an ILS Approach
- Entering Crossing Restrictions
- Unplanned Level<ff
- Extending the Final Approach Fix

Pilots' Knowledge Of The Functional Structure Of The System

The second phenomenon of interest is the pilots' knowledge of the functional structure of the FMS. By functional structure of the FMS we are referring to their 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 permit 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, and specific probes were developed for each subtopic (Table 2 summarizes the scenario probes).

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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 much affected by time pressure or concurrent tasks.

A. Knowledge of the CDU Page Architecture

The page architecture of the FMS control display unit contains a huge amount of data that may be relevant at some point during the flight. Since only a very limited set of data can be presented on the CDU screen at any given tune, 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:

- Single engine capabilities
- Wind data for fixes of flight
- Available fuel
- 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 CDU Descent Page to become the targets for their descent.

These probes were supposed 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/pages.

B. Mode Availability - Mode 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 ILS approach, pilots were asked to properly set up the FMS 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 glide slope 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.

The above probes allow us to determine whether pilots are familiar with the general prerequisites and procedures for engaging or disengaging a mode and whether they can apply this knowledge to a specific flight context.

C. FMC Logic

After takeoff from Los Angeles, pilots were asked to intercept the LAX 248 degree radial outbound. In order to successfully perform this task 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 that the FMS could fly to.

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 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 that the system automatically descends to.

D. Effects of partial system failures

During a descent, pilots were asked about the expected consequences of losing the autothrottles in that situation. 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 capturing the glide slope, the glide slope was failed due to a signal loss. This allowed us to test whether pilots would realize what happened, whether they would understand the implications of losing the glide slope, and how they would react to the failure. In addition, they were asked about the differences between a glide slope failure above versus below 1,500 ft AGL.

If the glide slope signal is lost above 1,500 ft, the G/S indicator and the F/D bars disappear from the ADI, and the aircraft continues its descent at the current rate of descent. A flag indicating unreliable glide slope input appears only on the standby attitude indicator. Glide slope loss below l,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).

E. 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 V/S mode, they also were asked what happens if an excessive rate of climb is used (i.e. the FMS automatically reverts to the LVL CHG mode to maintain a safe airspeed).

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

- Locating data in the CDU page architecture
- Tracking data propagation within the CDU
- Applying knowledge about mode capture criteria
- Disengaging the automatic APPR mode after capturing localizer and glide slope
- Intercepting a radial outbound
- Questions concerning VNAV Speed versus VNAV Path descent
- Loss of autothrottles during a descent
- Loss of G/S signal / G/S failure
- Predicting effects of excessive rate of climb in V/S mode
- Describing the different possible ways of doing a task

Mode Awareness

Table 3 summarizes the probes built into the scenario for testing pilots' mode awareness. They help determine whether pilots know who/which system is in dharge 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. In order to adequately cope with the situation, pilots have to understand what regime the autothrottles follow during takeoff. Until reaching 64 kts, the autothrottles will automatically go to N1. At and above 64 kts, pilots can manually override the autothrottles. Thus, if aborting the takeoff before 64 kts, the autothrottles have to be disengaged to prevent them from advancing again to reach N1.

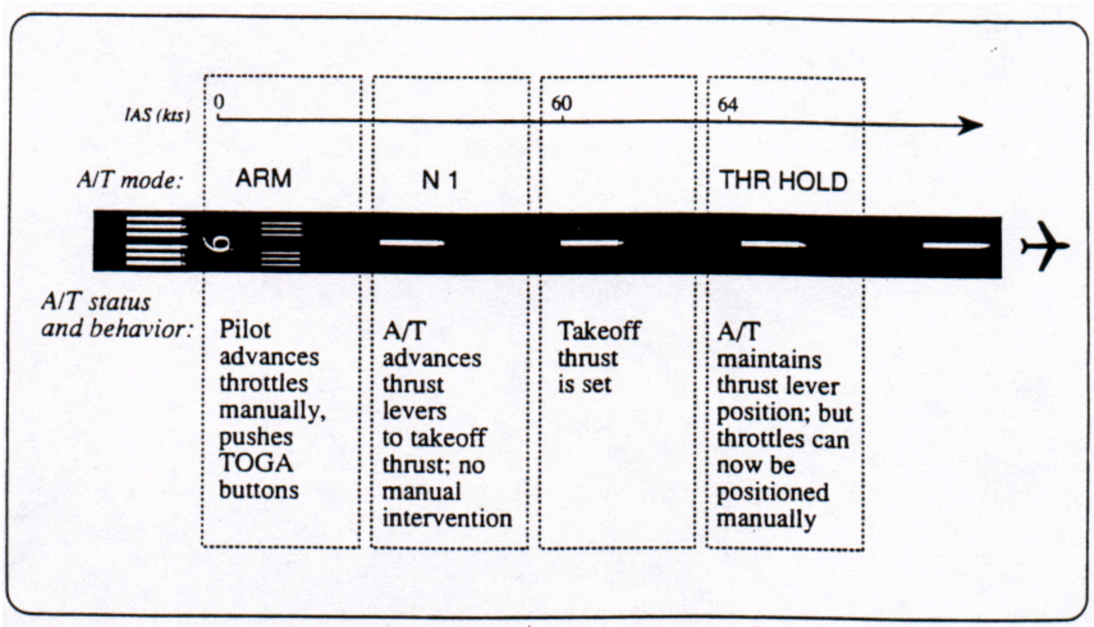

Figure 3. Autothrottle Status, Behavior, and Indications throughout the Takeoff Roll

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.

"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 requires that they 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 FMS-

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 activated the CONTROL WHEEL STEERING (CWS) pitch mode by pulling on the yoke, thus overriding the active LVL CHG pitch. The CWS pitch mode maintains the vertical rate that corresponds to the pilot-induced yoke position. The pilot-flying had to determine whether the aircraft would still level off at the target altitude that had been pre-selected on the Mode Control Panel for the LVL CHG mode.

<u>Anticipation of system status and behavior</u>

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. Scenario Probes of Pilots' Mode Awareness

- Aborted Takeoff below 64 kts
- Frequent changes in clearances involving mode transitions
- Tailwind in takeoff clearance
- Incorrect N1 manual setting
- Activation of CWS during climb
- Ask for predictions of ADI mode indications

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 they 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.

Table 4. Biographical Data and Flight Background of the Participating Pilots

	Experienced Pilots (n=14)	Transitioning Pilots (n=6)
Age [mean(std. dev.)]	41.1 (10.1) years	41.0 (4.0) years
Total Flying Time [mean(std. dev.)]	8,471 (4,539) hours	5,183 (1,273) hours
"Glass Cockpit" Experience [mean(std. dev.)]	1,011 (582) hours	0 hours

Procedure

Pilots were asked to fly individually a 60-minute scenario on a fixed-base B-737-300 part-task trainer. This simulator works based on an actual aircraft data base. It is equipped with all relevant cockpit instruments, and it allows for any operation except hand-flying the aircraft below 1,000 ft AGL.

Upon arrival 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 (see Appendix A). The participants were asked to take their seat in the cockpit, and to act as Pilot-Flying (PF) during this flight. They were given time to familiarize themselves with the cockpit set-up 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 set-up for the participant. He occupied the empty seat and acted as Pilot-Not-Flying (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 the following instructions:

- All FMS-related work has to be done by the PF (the participant) after activation of the autopilot at 1,000 ft AGL.

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

- 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 they 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 will deal with any significant differences between the performance of pilots with glass cockpit line-experience versus those without glass cockpit experience. For some tasks that allow pilots to choose among several different approaches, the preferred strategies for the two pilot groups will be presented. Finally, problems related to mode activation which occurred across different tasks are examined more closely.

Problematic tasks/events

Less than six 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/executing a holding pattern, installing an ILS approach, and entering crossing restrictions for waypoints along the route.

On the contrary, more than 14 pilots (70 %) showed deficiencies in performing the following tasks:

- Aborting a takeoff at 40 kts with A/Ts on
- Anticipating ADI mode indications throughout TO roll
- Anticipating when GA mode becomes armed throughout landing
- Disengaging APPR mode after LOC and G/S capture
- Explaining speed management for VNAV Path vs. VNAV Speed Descent
- Defining end of descent point for VNAV Path vs. VNAV Speed Descent
- Describing consequences of G/S loss above/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.

A. 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 (i.e. before THR HOLD is reached at 64 kts when the pilot can manually position the throttles), 16 pilots (80 %) described the procedure as follows: "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, 3 participants (15 %) realized that they had missed that item. Two pilots (10%) were not sure about this question and suggested that they would hold the A/Ts back manually, "just in case"[3]

Only 4 pilots (20 %) responded immediately by 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 one 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.

B. Anticipation of ADI indications during takeoff

[3] In 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 the FMS behavior, it seems unlikely that they would anticipate the need for manual intervention.

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, i.e., the autothrottles are in charge and will go to takeoff thrust, and THR HOLD, i.e., the aircraft has reached 64 kts, the autothrottles will go to takeoff thrust but 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. And another three pilots (15 %) could not predict any of the mode indications.

C. GA mode arm

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 glide slope capture.

D. Disengagement of the APPR mode after LOC and G/S capture

When asked to disengage the APPR mode after localizer and glide-slope had been captured, only 3 pilots (15 %) could recall the three ways of accomplishing this: either pushing the TOGA buttons on the throttles, turning both FDs and the A/P off, or retuning the VHF radio. 3even pilots (35 %) did not know of any procedure for disengaging the APPR mode. Three participants (15 %) were familiar with two of the three different options.

The solutions suggested by the remaining seven 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:

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

E. Speed Management and End of Descent Point – VNAV Path vs. VNAV Speed

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 vs. Speed descent, the results were similar. Twelve pilots (60 %) were aware of the end of descent during a VNAV Path descent, 9 pilots (45 %) knew at what point the VNAV Speed descent would end.

F. The consequences of a G/S failure above/below 1,500 ft

After GIS capture, a G/S signal loss was simulated at approximately 3,000 ft. Upon realizing the problem, pilots were asked about the consequences of this event. Fifty four per cent of the pilots could provide the correct answer. When asked whether a G/S failure at a lower altitude (below 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 was observed that it took some pilots a rather long time (in some cases, several minutes) to even realize the problem although 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 Versus Inexperienced Pilots

Major differences in performance between line-experienced versus transitioning pilots were seen only with respect to three of the tasks within the scenario.

When asked to intercept the LAX 248 degree radial, all 6 inexperienced pilots had difficulties carrying out the task using LNAV compared to only 50% of the 14 experienced pilots. None of the inexperienced pilots realized the need for building a fictitious waypoint on the radial. When asked about the consequences of using an excessive vertical rate of climb in the V/S mode, again 100 % of the inexperienced six subjects could not provide the correct answer compared to only 5 of the participants with line experience (36%). And finally, 83% of the six pilots without line experience could not describe how to program an intermediate descent on the VNAV CRZ 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 only allowed for one correct answer or reaction, some situations were built into the scenario that required that pilots 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.

<u>A. Intercepting a Radial outbound without a waypoint at a low altitude</u>

There are two possible methods for accomplishing this task. 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 %), while the pilots in transition to glass cockpits preferred to use LNAV (83 %)[4].While it is possible to use LNAV for this task, after one creates a fictitious fix outbound, MCP-VORLOC is the faster and easier method to do the job at low altitudes. It requires less pilot input and no heads-down time as compared to creating a fix using the CDU.

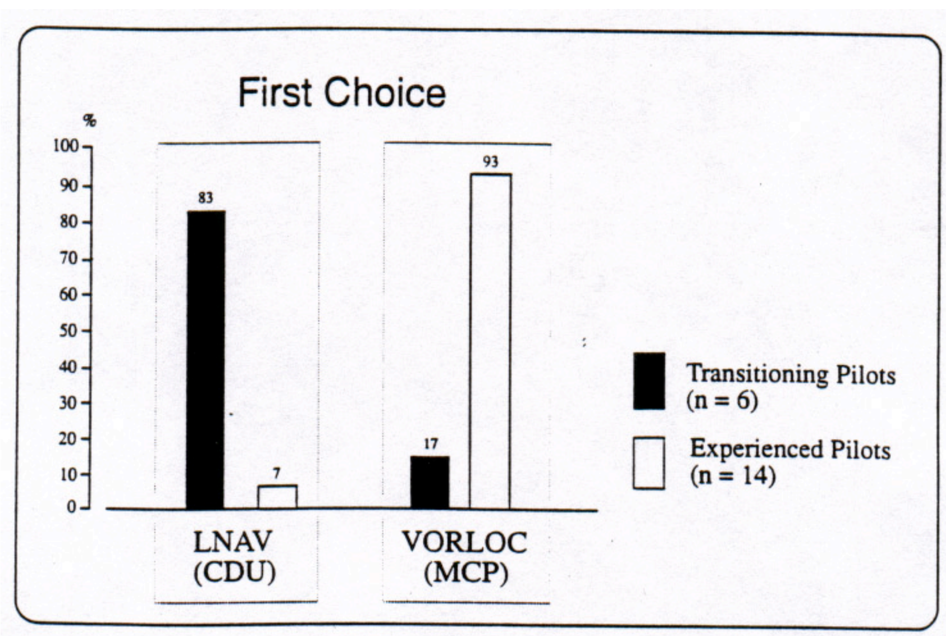

Figure 4. Preferred Mode and Level of Automation for Intercepting a Radial Outbound For Experienced versus Transitioning Pilots

[4] Some of the pilots in transition (16%) could not think of any second method at all.

B. 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 CLB page and activating the VNAV mode. In this case, all of the pilots in transition and 79 56 of the experienced glass cockpit pilots preferred the MCP-LVL CHG mode. Again, using the MCP minimizes heads down time, which is important as the aircraft is still at a very low altitude during this task.

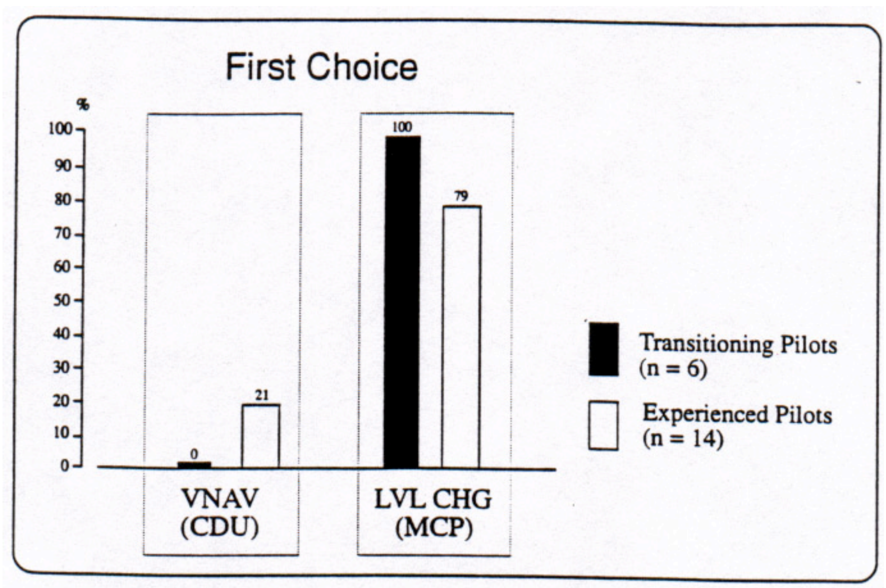

Figure 5. Preferred Mode and Level of Automation for a Speed-Restricted Climb at Low Altitude for Experienced and Transitioning Pilots

C. 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 CDU CRZ page and then activate VNAV. As Figure 6 shows, the majority of line-experienced pilots chose to descend using VNAV (79 9ro) while most of the less experienced pilots preferred to use the LVL CHG (MCP) mode (83 %). When asked why they preferred VNAV, the experienced pilots explained that, since 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.

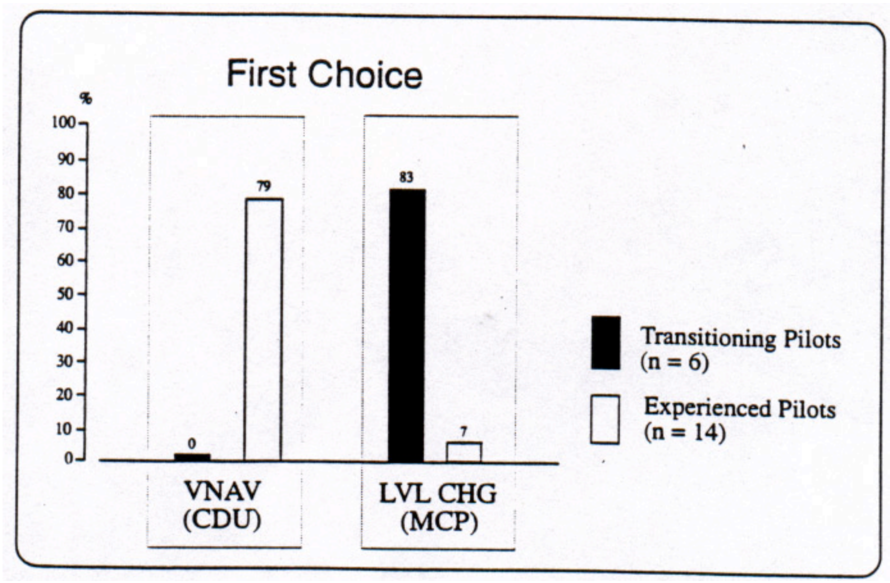

Figure 6. Preferred Mode and Level of Automation for an Unplanned Descent for Traffic at High Altitude for Experienced and Transitioning Pilots

Problems of Mode Activation

Another interesting result refers to failures to engage or re-engage a mode after entering (new) target values into either the MCP or the CDU. This omission occurred at least once during the scenario for 5 of the 6 transitioning pilots (the total number of omissions for this group was 9). Only two of the 14 experienced pilots forgot to engage an appropriate mode, and this occurred only once for each of them. The problem occurred four times in regard to the LNAV mode, six times with respect to the VNAV mode and once concerning the LVL CHG mode.

In seven of the failures to engage a mode, all required entries into the CDU or MCP were made, but no mode was activated. In the remaining four instances, the pilot would first use an MCP mode (e.g., HDG SEL) to get the system started towards the target, 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 in the majority of cases pilots forgot to engage VNAV or LNAV (rather than an MCP mode) after entering new target data may be related to the spatial separation between the data entry unit (CDU) and the VNAV- and LNAV-buttons which are located on the MCP.

Another problem related to mode engagement was the attempt to activate a mode without the prerequisites for this activation being met Three (50%) of the transitioning and one of the 14 experienced pilots tried to engage VORLOC without being in the manual radio mode as required. Three (50%) of the transitioning and 5 of the 14 experienced pilots engaged the APPR mode without lowering the MCP altitude first, and they were surprised to find that the aircraft did not start the descent.

DISCUSSION

This study verifies and expands on the results obtained from the previous corpus gathering studies of pilot-automation interaction (Sarter and Woods, in press). It confirms that most of the difficulties in pilot-automation interaction are related (a) to a lack of mode awareness and (b) to gaps in pilots' mental models of the functional structure of the automation. These kinds of problems seem to occur primarily in the context of non-normal time critical situations such as an aborted takeoff. Problems related to such situations may be under-reported in surveys because these situations rarely occur in line operations. In this study, however, every participant was forced to cope with non-normal 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 non-normal situations in the scenario—an aborted takeoff, the need to disengage an automatic approach mode for collision avoidance, and the loss of the glide slope 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 per cent 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 4 pilots responding correctly, and one of them did not seem to completely understand the basis for this action. Another non-normal time-critical event in the scenario was the request to disengage the APPROACH mode after localizer and glide slope capture. While most of the pilots knew about at least one way of complying with this request, 14 pilots also suggested at least one ineffective approach. If, in a real world case, ATC told the pilot to immediately change heading and/or altitude 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 indicates available options to help the pilot intervene quickly and directly when necessary. In the case of the third non-normal event in the scenario, the loss of the G/S during final descent, * was observed that it took many pilots fairly long to even realize that an anomaly had occurred, even though delay times could not be measured precisely. 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. 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, about one 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", i.e., the ability to anticipate future system behavior which 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. For example, only one out of 20 participants could predict the entire sequence of expected mode indications for the takeoff roll. Similarly, only five of the participants knew when to expect the indication that the Go-Around mode is now 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 have to a) have a thorough understanding of what a mode means in terms of system behavior and b) have to be "ahead of the FMS", i.e. they have to be able to anticipate future system behavior which can change not only in response to his own input but also as a result of changes in the environment or for protection purposes (see Reason, 1990).

Operational Costs of Technology Centered Automation

New automation is developed because of some payback (precision, more data, reduced staffing, etc.) for some beneficiary (the individual practitioner, the organization, the industry, 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. The new demands can include new or changed tasks (setup, operating sequences, etc.), and new cognitive demands are created as well. There are new knowledge requirements (e.g., how the automation functions), new communication tasks (e.g., instructing the automation in a particular case), new data management tasks (e.g., finding the relevant page within the CDU page architecture), new attentional demands (tracking me state of the automation), and new forms of error or failure (e.g., mode error). This study reveals some of these kinds of costs that occur in the context of the current generation of cockpit automation— costs that could 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 seem to be mode error and mode awareness.

Devices that allow some thing to be done one way in one mode and another way in another mode create the possibility of mode errors where 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 and Woods, 1992). 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,' i.e., he or she has to be able to anticipate future system behavior or detect system failures (Sarter and Woods, 1991). However, in this study, only five 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 (in press) is that many of the observed problems result from a lack of mode awareness—the pilots lost track of system targets and missed mode changes that occurred independent of immediate pilot commands. Maintaining mode awareness requires that pilot attend to and integrate data from a variety of indications in the cockpit such as the Flight Mode Annunciations on the Attitude Director Indicator, the visualization of the programmed route of flight on the Horizontal Situation Indicator, or the display of target values on the Mode Control Panel. 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 non-normal 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

The 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 the their understanding of the functional structure of the FMS. By forcing pilots to deal with various non-normal 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 and Woods, in press) and shows that these problems can occur even with pilots who have relatively extensive glass cockpit experience.

Note the interaction between two factors. 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. The lack of feedback on the state of the automation can in turn limit pilots' ability to learn from experience and correct or elaborate their mental models of system function over time. It also limits their ability to learn to perceive the state of the automation from the available indications. A third factor further complicates the difficulty. Many of 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 showed that sometimes pilots possessed knowledge in the sense of being able to recite the 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 will require scenarios and instruction designed around managing the transitions between different modes of automation. Third, since 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 in part due to lack of feedback about the state and behavior of the FMS). This means that an 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. Furthermore, there are some indications in the data that pilots are miscalibrated with respect to their understanding of the FMS, that is, the pilots may not be aware of the gaps in their mental models. An expert is well calibrated if they are aware of the areas and circumstances where they have correct knowledge and the areas where their knowledge is incomplete or limited. If the expert is overconfident and believes that they understand areas where in fact their knowledge is incomplete or limited, then that person is said to be miscalibrated (e.g., 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 modes and features of the FMS that I still don't understand' " (Wiener, 1989; Sarter and Woods, in press) 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 by the design of the scenario, 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 et al., 1991; Moll van Charante et al., 1992)

There are several factors that could contribute to the observed miscalibration. First, areas of incomplete or buggy knowledge can remain hidden from pilots because pilots 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 (e.g., Wagenaar and Keren, 1986). Problems with ineffective feedback on the state and behavior of the FMS that were observed in this study and reported in previous studies of pilot interaction with cockpit automation (e.g., Norman, 1990) could be a factor that contributes to poor calibration of pilots, i.e., a lack of awareness of the gaps in their mental models of the FMS. The relationship 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 * is widespread, is one factor that could lead to under-reporting 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 plot 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, how to switch from one mode to another smoothly. In other words, the pilots must know how the automated system works and he or she must develop skill at how to work the system. To meet the latter criterion, a pilot must:

- learn about all of the available options
- learn and remember how to deploy them across a variety of operational circumstances, especially rarely occurring but more difficult or more critical ones,
- learn and remember the interface manipulations required to invoke the different modes or features,
- learn and remember how to interpret or where to find the various indications about which option is active or armed and what are its associated target values.

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 and Woods, in press) and by studies of human-machine interaction in other domains (e.g., Rosson, 1983; Cook et al., 1990) 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 versus 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 just had finished their transition training were much less sensitive to these contextual factors. They tended to always use the highest level of automation independent of context.

Note that, in higher tempo phases of flight, more experienced pilots chose to use intermediate levels of automation which use the MCP as the interface over higher levels of automation that require CDU interaction. The MCP based modes generally require less interaction, less head down time, 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, activates a mode of control, 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 that pilots see the MCP and the CDU as separate systems (Sarter and Woods, in press) 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 pilots may vary 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. While 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 non-normal time critical situations. The severity and importance of these problems is underestimated due to several interacting factors:

- there are gaps in pilots' understanding of the functional structure of the automation,

- the opaque interface between pilots and automation makes it difficult for pilots to track the state and activity of the automation,

- pilots may not be aware of the gaps in their knowledge about FMS function,

- pilots can 'escape' from the CDU to the MCP whenever a situation gets too complicated or time pressure is too high, and

- the flight situations where these problems help produce unmistakable performance difficulties may occur infrequently in line observations.

The data m this study, in conjunction with the data from previous studies (e.g., Wiener, 1989; Norman, 1990; Sarter and Woods, in press), 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, but rather these problems result from limitations in how the automation and the human pilots are integrated together as a joint, distributed cognitive system (Hutchins, 1991; Woods, 1993).

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