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# "Strong, silent, and 'out-of-the-loop'": Properties of advanced (cockpit) automation and their impact on human-automation interaction

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The Ohio State University, 1994



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# *"STRONG, SILENT, AND 'OUT-OF-THE-LOOP' ":*

# PROPERTIES OF ADVANCED (COCKPIT) AUTOMATION AND THEIR IMPACT ON HUMAN-AUTOMATION INTERACTION

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
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By

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1994

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# CHAPTER I

## INTRODUCTION

In a variety of domains, the development and introduction of advanced[1] automated systems has increased the efficiency, precision, and safety of operations. At the same time, however, unexpected problems with human-automation interaction have been observed that are related to the "communication *with* machines rather than operation *of* machines" (Card, Moran, and Newell, 1983). Effective communication and cooperation with advanced automated systems is critical as they are no longer passive tools but rather agent-like machines that involve a high degree of complexity. They provide a large variety of interacting modes, i.e., different options for performing a certain task. Highly evolved automated systems operate at a high level of autonomy and authority (Billings, 1991; Sarter and Woods, 1994). They can initiate actions without immediately preceding operator input -- autonomy, and they are capable of modulating or overriding user input -- authority. These properties of modern technology require that the operator maintains a high level of awareness of the automation status, behavior, intentions, and limitations in order to efficiently coordinate his activities with the system. The automation involves yet another quality that interferes with effective cooperation -- low observability (Woods et al., in press). The automation interface is not designed for assisting

[1]The term 'advanced' refers to the increased capabilities of these systems and to their high level of autonomy and authority as discussed in Chapter II of this document.

the operator in monitoring its status and behavior in all circumstances. This 'strong and silent' nature of some automated systems is considered to be one contributor to observed breakdowns in human-machine cooperation and coordination due to a lack of mode awareness, i.e., due to a lack of knowledge and understanding of the current and future status and behavior of the automation (Sarter and Woods, in press). A lack of mode awareness can result in mode errors and in so-called 'automation surprises' where a mismatch is detected between expected and actual system behavior. These automation surprises tend to occur primarily in the context of highly dynamic or non-normal situations that tax the human's attentional resources and abilities and therefore involve a high risk of losing track of system behavior (Sarter and Woods, 1994; Woods et al., in press).

Mode errors and 'automation surprises' are the result of a mismatch between the properties and abilities of both human and machine. Therefore, differences in system design can be assumed to have an impact on the nature of problems encountered by operators. Natural variations in system design exist in the form of systems that implement different automation philosophies or that belong to different generations of automation technology (Billings, 1991). In other words, the term "automation" comprises a wide variety of systems that differ with respect to their capabilities and design features. Surprisingly, automation-related research rarely acknowledges the importance of such differences but rather operates under the assumption that the term 'automation' refers to a homogenous group of systems.

The objective of this research is to explore whether recent trends in automation design towards higher levels of system authority and autonomy without a parallel increase in system observability create the potential for new kinds of errors. The reported research focuses on the aviation domain where the development and introduction of increasingly 'strong and silent' automation is rapidly progressing. Results of previous research on pilot interaction with earlier generation cockpit automation are available for comparative purposes (e.g., Wiener, 1989; Sarter and Woods, 1992, 1994). The focal point of this research is pilot interaction with one of the most advanced automated aircraft currently in operation. This aircraft exemplifies the above outlined trend towards high levels of authority and authority without increased observability.

The described project involves a converging operations approach. First, pilot training for the aircraft was completed at the cooperating airline for the purpose of familiarization with the aircraft and its field of operation. Subsequent observations of training and line operations served the exploration of pilots' strategies of and problems with learning about and using the aircraft automation. A survey of airline pilots flying the advanced aircraft was carried out to gather a corpus of automation-related surprises in order to learn about the nature and circumstances of the most frequently encountered difficulties. The analysis of these data revealed different categories of mode-related problems which were instantiated in the scenario for a subsequent experimental simulation study. Experienced pilots flew the scenario on a full-mission simulator to examine whether pilot-reported problems would in fact be experienced by pilots in situ, to observe whether or not and under what circumstances pilots would detect and recover from mode errors, and whether unexpected difficulties would be observed.

CHAPTER II

# THE EVOLUTION OF AUTOMATION PROPERTIES AND THEIR IMPACT ON MAN-MACHINE INTERACTION

## 2.1 Autonomy, Authority, and Observability: The Evolution of Critical Automation Properties

The term automation is often used as though it refers to a homogenous class of systems when, in fact, these systems differ with respect to critical properties such as their level of complexity, authority, autonomy, or observability. Such differences exist due to different automation philosophies adopted by different manufacturers and because of the rapid evolution of automation technology over time.

A recent trend in automation design seems to be increasing levels of system autonomy and authority without a parallel increase in system observability. The first important property, a high degree of autonomy, refers to the capability of advanced systems to carry out long complex sequences of actions without requiring immediately preceding pilot input once they have been preprogrammed and engaged (Woods, 1993). This independence is made possible by the fact that modern systems can change their behavior in response to input from a variety of sources including various operators, sensors of the environment, and designer instructions (Reason, 1990). This property presents the operator with the challenging task to keep track of all possible sources of input and of the consequences of their input on system status and behavior.

Advanced systems also involve a high level of authority, i.e., the power to control and command actions. An example of high authority in the aviation domain which is the focus of this research are so-called 'envelope protection' functions on advanced automated aircraft. Envelope protection refers to the ability of the automation to detect and prevent or recover from predefined unsafe aircraft configurations (e.g., a stall). Once an undesired configuration is approached or detected, the automation has the power to override or limit pilot input.

Autonomy and authority are highly coupled system properties. Authority presupposes a certain degree of autonomy; and system autonomy without authority is likely to create a situation where the system operator has to interrupt his activities to check the feasibility and adequacy of every system-proposed action and then communicate his (dis)agreement to the system. This cumbersome approach to the cooperation between man and machine has been discussed under the label 'management by consent' (Billings, 1991). It reveals the "dilemma of delegation": "if automation and team work are supposed to reduce the burden on the operator by taking over and sharing tasks, then it seems counterproductive to require that all input be checked and agreed to by every member of the team" (Woods et al., in press).

Increasing levels of system authority and autonomy lead to a fundamentally new role of the automation in the overall system -- the automation is no longer just a tool but rather represents a new agent. As a consequence, it becomes much more important for man and machine to communicate about their intentions, actions, and limitations and to coordinate their activities. An additional resource management task is created for the operator.

In order to support this new task, a third trend in automation design towards increased system observability would be necessary. Advanced systems would need to possess improved communicative abilities in the sense of knowing when to share information with the human, how to present information on its status and behavior, and what information is critical in what circumstances (Winograd and Flores, 1988; see also Johannesen, 1994). But the development of feedback design has not kept pace with these requirements created by the evolution of powerful agent-like systems. Advanced automation tends to provide the same kind of feedback as its predecessors. On some flight decks, the design of displays and controls has changed. However, it is not clear what effect these changes have on the observability of the system, i.e., on the extent to which the system supports the monitoring of its status and behavior.

The problem with system observability is not a lack of feedback. In fact, the amount of available data on many advanced systems has increased dramatically. But mere data availability does not guarantee that critical information can be located and used by the operator in a timely and efficient manner (Woods, 1993). One example of changes in current feedback design is that more and more data are presented in the visual mode while previously available tactile and auditory cues are removed. Such a design fails to acknowledge and exploit the human's ability to process information in parallel provided it is presented via different sensory channels.

To summarize, advanced automated systems involve high levels of authority and autonomy. Their resulting agent-like behavior requires increased coordination between human and machine which, in turn, makes it necessary for the system operator to maintain a high level of awareness of the activities and intentions of the automated system (Billings, 1991). A lack of improvement in feedback design, however, does not seem to support and sometimes even counteracts this need for communication and cooperation. The following figure illustrates these opposing trends in automation design and their impact on human-machine coordination.

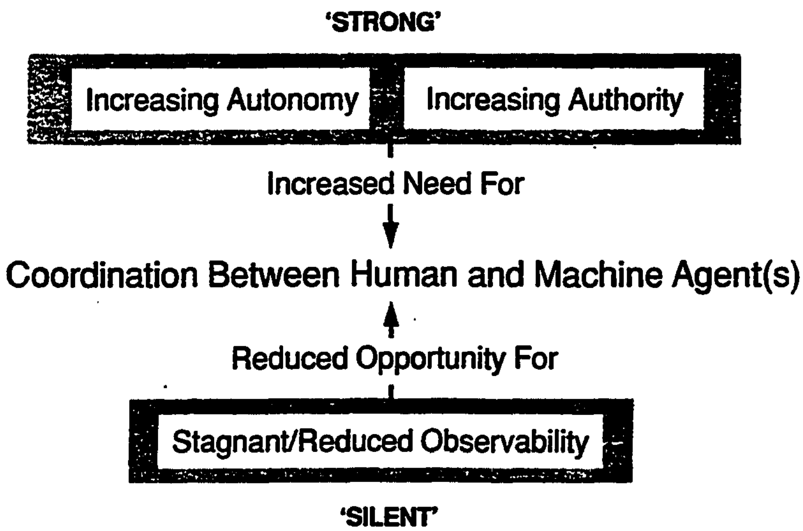



Figure 1. Opposing Trends in Automation Design and Their Impact on Human-Machine Coordination

The objective of this research is to investigate whether these recent trends in automation design have indeed created the predicted potential for new kinds of problems with human-machine interaction. One field of practice in which this question can be examined is the aviation domain. It represents an area where the rapid evolution of technology has led to the introduction of aircraft that involve highly powerful and independent yet 'silent' automation.

## 2.2 Problems with Pilot-Automation Interaction on Automated Flight Decks: Mode Errors and 'Automation Surprises'

The aviation domain is one of the areas where the evolution of automation technology is proceeding rapidly. As in other fields of practice, automated systems that were introduced to the flight deck of modern airliners have yielded benefits in terms of safety and efficiency of operations. Systems like the Ground Proximity Warning System (GPWS) or Windshear Detection systems have improved the safety of air transport. Fuel efficient power plants and more efficient lateral navigation systems are contributing to more economical operations (Wiener and Curry, 1980). At the same time, however, unanticipated problems with the interaction between pilots and some advanced cockpit systems are being reported and observed.

Warnings of potential problems with cockpit automation were voiced as early as the late 1970s (e.g., Edwards, 1977), and concerns have been fueled ever since by incidents and accidents involving automated aircraft (e.g., Lenorovitz, 1990; Sparaco, 1994), by pilot reports of difficulties that are experienced during training and line operations (e.g., Eldredge et al., 1991; Sarter and Woods, 1992), and by the results of empirical research on pilot-automation interaction (e.g., Wiener, 1989; Wiener et al., 1991; Parasuraman et al., 1993; Sarter and Woods, 1994). Since the early days of cockpit automation, some major areas of concern have been pilot workload, pilot error, excessive trust in automation, and pilots' manual flying skills (Norman and Orlady, 1989; Wickens, 1994; Wiener, 1989).

More recently, with the introduction of increasingly complex systems to the flight deck, new kinds of problems related to the communication and coordination between pilots and cockpit systems have provoked considerable interest -- mode errors and related 'automation surprises' (Sarter and Woods, in press). What is the nature of and the basis for these kinds of difficulties ?

In the late 1970s, so-called Flight Management Systems (FMS) were developed and introduced to the flight deck of modern airliners. These highly complex and powerful systems can handle a variety of tasks for the pilot such as navigation, flight path control, or aircraft systems management. They involve a large variety of interacting levels and modes of operation. These systems allow the pilot to choose from a continuum of operations ranging from fully manual control to a combination of manual and various automated modes to fully automated flight. The term "mode" in this context refers both to the status and behavior of the automation. While the large variety of options has the advantage of providing pilots with a high degree of flexibility, it also contributes to observed problems as it imposes new cognitive demands on the pilot. He needs to know about, select from, and monitor all the different possible automation configurations.

Previous research has shown that inadequate system feedback as well as gaps and misconceptions in pilots' knowledge and understanding of the automation can lead to breakdowns in mode awareness, i.e., to a lack of knowledge and understanding of the current and future status and behavior of the automation (Sarter and Woods, 1994; Woods et al., in press). A lack of mode awareness can lead to mode errors where the operator carries out an action that would be appropriate for one mode of the system when, in fact, the system is in a different mode. The detection of the resulting discrepancy between expected and actual outcome of the pilot's input creates an 'automation surprise'.

Our current understanding of these difficulties with pilot-automation interaction is based on studies that focused on a rather early generation of automated aircraft such as the B-757/767 (Wiener, 1989) or the B-737-300/400 (Sarter and Woods, 1992, 1994). These studies showed that pilots sometimes lose track of automation behavior and experience difficulties with directing the automation, primarily in the context of highly dynamic and/or non-normal situations. In most cases, these problems are associated with errors of commission, i.e., with errors that require a pilot action in order for a problem to occur.

These studies focused on aircraft that were built by the same manufacturer, based on the same philosophy of automation, and that involved a similar interface design. Therefore, the question whether their results apply to more advanced aircraft that were fielded in the late 1980's and early 1990's (e.g., the MD-11, the Airbus A-320, or the B-747-400) remains unsettled. The automated systems on these aircraft differ from earlier automation with respect to their increased level of autonomy and authority. This trend toward more powerful independent systems would have to be paralleled by the development of improved system feedback in the interest of effective communication and coordination between humans and these agent-like machines. However, very few aspects of feedback design on advanced flight decks have changed, and it is not clear whether these changes contribute to improved observability. To study the impact of new automation design on human-machine cooperation and coordination, this research project examines the nature of and the underlying reasons for problems with mode awareness and with pilot-automation coordination in the context of one of the most advanced automated aircraft currently in operation, the Airbus A-320.

CHAPTER III

# THE FLIGHT DECK OF THE AIRBUS A-320: AN EXAMPLE OF ADVANCED AUTOMATION TECHNOLOGY

In the preceding chapters, mode awareness was introduced as one of the major prerequisites for safe and efficient coordination and cooperation between pilots and cockpit automation. Breakdowns in mode awareness can lead to 'automation surprises' and mode errors which are inherently symptoms of a mismatch between man and machine. Their nature and underlying reasons are closely related to the system context in which they occur. It is therefore not clear that results of previous research which focused on pilot interaction with earlier generations of automated aircraft (e.g., Wiener, 1989; Sarter and Woods, 1992, 1994) apply to the more advanced cockpit technology implemented on aircraft such as the MD-11, the B-777, or the Airbus A-320. To explore what impact properties of advanced technological systems may have on the nature of and reasons for problems with the coordination between pilots and the automation, this research project examines issues related to mode awareness and pilot-automation coordination on one of the most advanced aircraft currently in operation, the Airbus A-320. The automation on this aircraft (as on other advanced airplanes like the MD-11 or B-777) involves a higher level of authority and autonomy than automated systems on the B-737-300/400 or the B-757. At the same time, the observability of the automation does not seem to have improved with the evolution of these more powerful systems, thus widening the gap between required and available feedback on advanced aircraft.

It is important to keep in mind that this study employs the Airbus A-320 as a natural laboratory representing the properties and capabilities of the most advanced automated aircraft -- it is not a study about one particular airplane. Details about the operation and functional structure of the A-320 automation will only be provided for the purpose of illustrating concepts and to help the reader understand the 'automation surprises' and scenario events that are laid out in later sections of the report.

## 3.1 The Airbus A-320

In the early 1980s, advances in computational technology allowed designers and engineers to start incorporating logic into airplanes. Among the first 'glass cockpit' aircraft [the term 'glass cockpit' refers to the replacement of traditional analog round-dial gauges by cathode-ray tubes (CRTs) for the presentation of flight-related information] that involved built-in processing power were the Boeing B-757, the Boeing B-767, and the Airbus A-310. In 1988, the Airbus A-320 was introduced which represented a major step up in terms of the autonomy and authority of cockpit automation. It also involves a drastically different design of flight controls and system feedback from other civilian aircraft.

One major difference between the automation on other aircraft and on the A-320 is its very high level of authority as illustrated by its so-called 'envelope protection' functions. Envelope protection prevents the pilot from exceeding the structural limits of the airframe by overriding and limiting his input. For example, independent of pilot input, the airplane will not exceed a certain pitch or bank angle in most flight regimes. This is possible because the A-320 is flown by means of digital controls ("fly-by-wire"). Pilots' input is sent to several flight control computers which calculate the necessary and allowable adjustments to the flight control surface positions. These computers send their commands to hydraulic actuators which then actually move the control surfaces.

While envelope protection functions on the A-320 were introduced to increase safety by preventing undesirable or dangerous aircraft configurations (such as a stall), they are criticized for involving so-called 'hard limits', i.e., limits that pilots can override only by means of turning off more than one of any of the redundant types of flight computers on the aircraft. In other words, envelope protection is considered to provide too much authority to the automation (see Billings, 1991). Other advanced 'glass cockpit' aircraft such as the B-777 or the MD-11 involve 'soft limits' that allow pilots to override the protection limits more easily and directly by applying additional control force to the flight controls when necessary.

The envelope protection functions on the A-320 also illustrate the high degree of autonomy of advanced cockpit technology. The recovery activities of the automation are triggered by input from sensors of the airplane configuration, and the nature of the recovery actions is determined by the system designer. In other words, envelope protection is an example of system behavior that occurs independent of pilot input. To ensure that the pilot can still maintain mode awareness in the interest of coordinating his activities with those of the automation, it is necessary to promote system observability by providing improved indications of automation status and behavior.

Previous research on early generation 'glass cockpit' aircraft that require less communication and coordination than today's advanced flight decks has shown that system observability is insufficient to keep track of the status and activities of the less autonomous systems on those aircraft (see Eldredge et al., 1991; Wiener, 1989; Sarter and Woods, 1992, 1994). With the introduction of more advanced independent automation, the need for effective feedback has increased as pilots need to maintain a high level of system awareness in order to be able to coordinate their activities with the agent-like automation. However, the development of system feedback has not kept pace with the increasing demand. Fundamental problems associated with feedback on earlier generation automated aircraft such as the fragmentation of information across numerous displays in the cockpit or the focus on indications of status rather than behavior have not been eliminated on modern flight decks. Details of the feedback design have changed but it is not clear what the effects of these changes are. In some cases, previously available cues have been removed. For example, on the Airbus A-320, the traditional yoke has been replaced by sidesticks which are not cross-coupled and do not move when under automation control. Therefore, pilots no longer receive visual or tactile feedback directly from the flight controls to help them keep track of the other pilot's or the automation input.

The A-320 also features a different design in terms of thrust controls and management. In manual operations, the A-320 thrust levers operate like conventional throttles. When autothrust is in control, however, the thrust levers are placed into one of five detent positions (Reverse Idle, Idle, Climb, Maximum Continuous Thrust/FLEX Takeoff, Takeoff/Go-Around) which define the maximum amount of thrust desired by the pilot (see figure 2). The automatic thrust management system called FADEC (Fully Automatic Digital Engine Control) varies thrust between idle and this pilot-determined maximum setting to comply with pilot-commanded or automation-computed targets for speed and vertical navigation. When controlled by the FADEC system, the thrust levers do not move and thus do not provide the pilot with any visual and/or tactile feedback about thrust settings. Instead, indications of commanded and actual thrust as well as other engine parameters are available on the upper ECAM (Electronic Centralized Aircraft Monitoring System) display only (for a discussion of benefits and disadvantages of the A-320 autothrust design see e.g. Last and Alder, 1991).

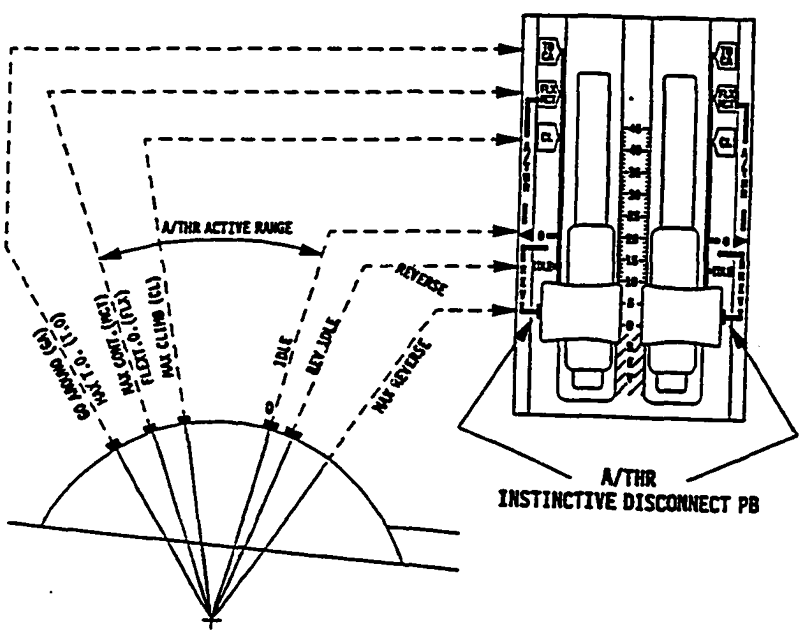



Figure 2. The Design of the Throttle Quadrant on the Airbus A-320

## 3.2 Introduction to the Flight Management and Guidance System

This research focuses on one of the core systems of cockpit automation - the Flight Management and Guidance System (FMGS). The following section provides a brief, simplified overview of the A-320 FMGS that supports pilots in a variety of tasks related to flight management such as flight planning, navigation, performance management, information display, and flight progress monitoring. Its second major function is flight guidance which includes providing autopilot commands, flight director commands, and autothrust commands. Finally, the FMGS also handles flight augmentation functions such as providing rudder commands and computing flight envelope parameters.

The major FMGS controls in the cockpit are the Flight Control Unit (FCU), the multifunction keyboards of two Control Display Units (MCDU) (one for each pilot), the sidesticks, and the thrust levers. FMGS-related cockpit displays are the two MCDU multifunction displays, two Primary Flight Displays (PFD) which provide nominal indications of the active and armed automation modes (flight mode annunciations -- FMAs), and two Horizontal Situation Indicators (HSIs) which are also called map displays. Figure 3 illustrates the location of these different FMGS components in the cockpit.

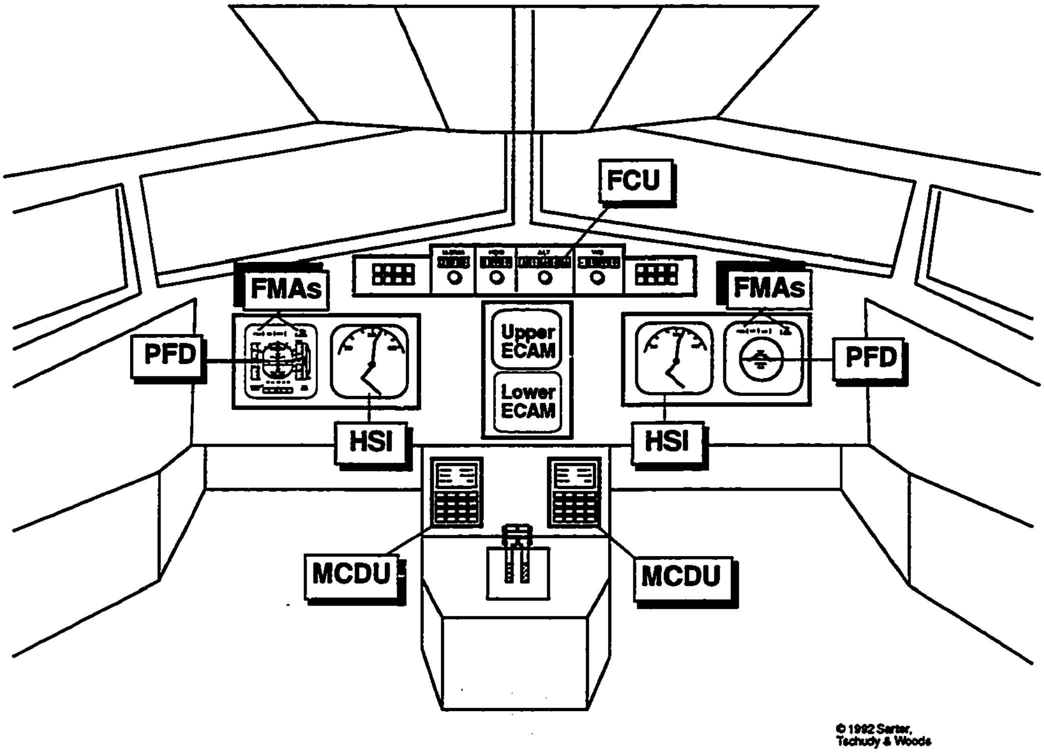



Figure 3. Flight-Deck Controls and Displays Related To Pilot-FMGS Interaction in a Generalized 'Glass Cockpit'.

The Control Display Units (M(ultifunction)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 numerous pages within the MCDU page architecture. The pilot-entered flight path is continuously updated to reflect the current flight status, and it is presented on the HSI. This feedback allows pilots to monitor progress along the path. The Flight Control Unit is used to activate different automatic flight modes (e.g. Open Descent, Vertical Speed, Heading Select). The pilot can also use knobs on the FCU to dial in targets for individual flight variables (airspeed, heading, altitude, and vertical speed) which are tracked by the system if a corresponding automatic flight mode is activated. To find out which FMGS modes are currently active, the pilot can refer to the flight mode annunciations (FMAs) on the Primary Flight Display (PFD). These provide data on the active (or armed) pitch, roll, and thrust modes as well as on the autoland capability of the aircraft and on the status of the autopilot(s), flight director(s), and autothrust system.

The various FMGS interfaces and autoflight functions provide the pilot with a high degree of flexibility in terms of selecting and combining numerous levels and modes of automation to respond to different situational requirements. This flexibility is beneficial for pilots; however, it also creates a new burden for them – they have to know about, select among and track transitions between the many different modes that are potentially available. The complexity of the mode situation on the A-320 is illustrated by the following figure showing all possible flight mode annunciations on the Primary Flight Display.

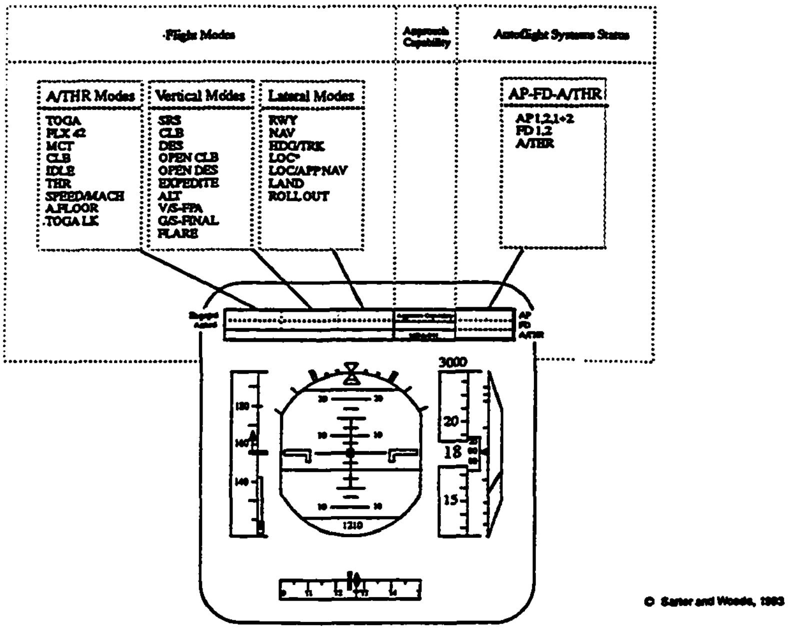



Figure 4. An Example of Mode Complexity As Indicated By the Flight Mode Annunciations on the Primary Flight Display

It is important to note 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 *managed* vertical and lateral navigation. 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 MCDU, and then activate the automation by pushing the FCU altitude, speed, and/or heading knob. The Flight Management and Guidance Computer (FMGC) automatically controls the aircraft to follow the desired flight path. At this strategic level of automation, the FMGS pursues a sequence of target values without the need for further intervention by the pilot. This function 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), 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 Flight Control Unit (FCU). He then activates one of the corresponding modes by pulling the respective FCU knob, thus activating a *selected* guidance mode; the target will be captured and maintained automatically until target or mode of control are actively changed by the pilot.

A high degree of dynamism represents one important characteristic of automatic flight path control. Transitions between modes of control occur in response to both pilots' input and to changes in flight status and environment. 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 FMGS 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 Primary Flight Display, the visualization of the programmed route of flight on the Navigation Display, and the displayed target values on the Flight Control Unit.

# CHAPTER IV

## AN EMPIRICAL STUDY OF PILOT-AUTOMATION INTERACTION ON THE AIRBUS A-320

The preceding chapters have introduced the reader to the current state of knowledge concerning problems with pilot-automation interaction on early generation 'glass cockpit' aircraft. Mode errors of commission and resulting 'automation surprises' were shown to be major difficulties encountered by pilots on these aircraft. Given that mode errors can be seen as symptoms of a mismatch between properties of both the human and the machine, new attributes of more advanced (cockpit) automation were discussed in terms of their potential for creating new requirements and problems with respect to human-machine communication and coordination. To examine whether the current trend in automation design towards higher levels of authority and autonomy without a parallel increase in observability does in fact create the opportunity for new kinds of difficulties, this research has studied pilot interaction with automated systems on one of the most advanced flight aircraft currently in operation, the Airbus A-320. A short description of the automation on this aircraft was provided to familiarize the reader with its basic elements, capabilities, and functional structure.

The following sections will describe the procedures and results of two complementary research activities that were carried out to examine the nature and circumstances of automation-related problems encountered by A-320 pilots during line operations. First, a survey was conducted to gather a corpus of pilot reports on the nature and circumstances of problems with the advanced automated systems on this aircraft. An analysis of these reports suggests that mode errors and automation surprises also occur on this highly advanced flight deck. They seem to be the result of mismatches between pilots' expectations of and the actual behavior of the automation. Different reasons for mismatches were identified and instantiated in the scenario for a subsequent experimental simulation study in which experienced A-320 pilots were confronted with tasks and events that are considered to involve a high potential for surprises. This study served to investigate whether pilots would in fact experience problems with these scenario elements, what the nature of these problems would be, and how pilots would cope with the encountered difficulties. An important objective of the experiment was to explore whether pilots have difficulties detecting unanticipated changes in the status and behavior of the automation due to their monitoring strategy, which they describe as being expectation-based.

## 4.1 Methodological Approach

This research project involves a converging operations approach, starting out with completion of the A-320 training program at the cooperating airline and with observations of A-320 training and line operations. These activities served the purpose of familiarization with the airplane, its systems, and its operation at the cooperating carrier. They also provided first insights into problems experienced by pilots flying the A-320 on the line or transitioning from a conventional airplane to the Airbus A-320.

Next, a survey of A-320 pilots was conducted to gather a more systematic corpus of problems and experiences with as well as strategies of using the A-320 automation during line operations. This survey expands on the results of previous studies which showed that 'automation surprises' were experienced by pilots with a considerable amount of experience on earlier generation 'glass cockpit' aircraft (Wiener, 1989; Sarter and Woods, 1992). The questionnaire used in this study serves to explore whether pilots on the more advanced flight deck of the A-320 also encounter surprises related to automation behavior, and, more importantly, to gather information on the nature and circumstances of these surprises by asking pilots for detailed descriptions of these events. Finally, the survey represents a first step in examining pilots' monitoring strategies on advanced flight decks. A better understanding of these strategies is critical for identifying factors that contribute to breakdowns in mode awareness and for developing measures that can support pilots in keeping track of the status and behavior of the automation.

The corpus of pilot reports concerning automation surprises was analyzed to identify categories of mode-related problems that seem to share common underlying reasons. These categories provided the basis for the design of a scenario for the final step in this line of research -- an experimental simulation study of pilots' mode awareness and coordination with advanced cockpit automation. In this study, experienced A-320 pilots were confronted with instantiations of the problem categories suggested by the survey to find out whether these tasks and events would in fact create problems for pilots and to examine how participants in the study would cope with these autoflight-related challenges.

The use of various different research techniques in this project serves to provide converging evidence concerning problems with pilot-automation interaction by adopting different perspectives (e.g., observer, trainee, experimenter) and by progressing from exploratory activities to an increasingly focused and controlled collection of empirical data. This approach acknowledges the fact that different research techniques are suited best for different purposes, and it helps compensate for the weaknesses of each individual technique.

For example, subjective data gathered by means of knowledge elicitation techniques like a pilot survey involve a variety of problems. Pilots' motivation for responding to the survey is not clear but may determine the nature of comments and result in a body of misleading data. Also, subjective data can be ambiguous due to a lack of calibration on the part of the respondents with respect to their own proficiency and system knowledge (Wagenaar and Keren, 1986). For example, certain problems with automated systems may be underreported because they involve situations that occur very infrequently and therefore have not yet been encountered by many respondents.

To compensate for these weaknesses and to gather complementary data, the experimental simulation study of pilots' mode awareness and pilot-automation coordination on the A-320 was carried out as the last step in this line of research. The advantage of an experimental simulation study is that it goes beyond the mere observation of naturally occurring undisturbed behavior but rather involves the manipulation of behavior by setting up specific probes and events in a behavioral setting that mirrors the most important task-relevant aspects of the naturally occurring target setting. In other words, it allows us to create and force actual behavior rather than rely on its subjective description.

## 4.2 A Survey of A-320 Pilots

A questionnaire was developed and distributed to all A-320 pilots (n=750) at one major U.S. airline. This questionnaire asked pilots about their experiences with the training for and the operation of the A-320 automation during line operations. Only part of this questionnaire (questions 1a) and 1b) and 6a)) was developed specifically for the purpose of the research reported in this document (see Appendix A). Pilots were asked about the occurrence and nature of 'automation surprises' during line operations and about their strategies of information gathering on the A-320. In other words, the survey focuses on strategies for and breakdowns in monitoring the automation which seem to form the basis for observed and reported problems with mode awareness.

Pilots returned their responses directly to the Cognitive Systems Engineering Laboratory at the Ohio State University. To guarantee confidentiality and anonymity of the data, pilots were asked not to include any identification on their responses.

### 4.2.1 Background Information

The following table provides an overview of the age and flight background of pilots who responded to the survey.

Table 1. Background and Flight Experience of Pilots Responding To The Survey (n=169; 22.5%)

| | |
|---|---|
| Age (n=168) | 41.4 (6.5) yrs [mean (SD)] |
| Total flight time (n=168) | 10,191 (5,064) hrs<br>[mean (SD)] |
| Time on the A-320 (n=164) | 1,129 (695) hrs [mean (SD)] |
| Seat on the A-320 (n=167) | Captain 90 (54%)<br>First Officer 77 (46%) |
| Aircraft flown before transitioning to A-320 (n=165) | DC 9 60 pilots<br>B 727 44<br>B 757 22<br>B 747 13<br>B 747-400 10<br>DC 10 7<br>MD 80 4<br>F 16 2<br>RF 4 1<br>DA 50 1<br>SA 227 1 |
| Do you have any prior glass cockpit experience at all? (n=166) | Yes 66 (39.8%)<br>No 100 (60.2%) |

### 4.2.2 "Automation Surprises" on the Airbus A-320

Previous research on pilot-automation interaction has shown that pilots sometimes experience so-called "automation surprises" where the automation shows unexpected behavior or fails to take anticipated actions (e.g., Wiener, 1989; Eldredge et al., 1991; Sarter and Woods, 1992). Those studies focused on aircraft that were less advanced than the A-320 and that were built by a different manufacturer based on a different automation philosophy. It was therefore important to establish whether or not and what kinds of automation surprises were experienced by A-320 pilots. Pilots were asked for detailed reports of up to three situations in which they were surprised by the automation, and they were also asked whether or not and how they managed to explain what had happened in those situations.

Knowledge about the nature and circumstances of surprises is important because it helps understand why surprises occur, and it illustrates how differences in automation design can affect the kinds of problems encountered in pilot-automation interaction. Information on the nature of surprises also served as an important source of input for the design of a scenario for the subsequent experimental simulation study of pilots' mode awareness and coordination with the automation on the A-320.

The following table shows a) the responses of the overall group of A-320 pilots and b) a comparison of responses by pilots with versus those without prior 'glass cockpit' experience with respect to the question whether or not they have ever experienced automation surprises on the A-320.

Table 2. Pilots' Responses to "Have you ever been surprised by the automation on the Airbus A-320?" (n=167)

| | All Pilots | Prior Glass | No Glass |
|---|---|---|---|
| Yes | 133 (80%) | 52 (79%) | 78 (80%) |
| No | 34 (20%) | 14 (21%) | 20 (20%) |

The majority of responding A-320 pilots (80%) has been surprised by the automation at least once during line operations. This result confirms and even exceeds the finding of a different study concerning pilot-automation interaction on the B-757 showing that 60% of pilots on this different 'glass cockpit' aircraft were sometimes surprised by their automation (Wiener, 1989). A similar result was also found by Sarter and Woods (1992) in their survey of B-737-300/400 pilots where 67% of the responding pilots indicated that the behavior of the automation sometimes surprised them.

It is important to note that there is no significant difference between the responses of A-320 pilots with versus those without prior 'glass cockpit' experience. In other words, the same percentage of pilots in both groups - about 80% - have been surprised by the automation. This result was not expected as previous studies seem to suggest that prior 'glass cockpit' experience reduces the likelihood of surprises (see Sarter and Woods, 1992). A possible explanation for this result is that previous studies of pilot-automation interaction involved pilots whose prior experience with advanced cockpit technology was gathered on aircraft with a very similar type of cockpit automation. In contrast, prior 'glass cockpit' experience of pilots in this study was gathered on aircraft that involve a different kind of automation design than the Airbus A-320. Their prior experience may therefore not be useful or even result in negative transfer across aircraft leading to inadequate expectations and additional surprises on the A-320.

Pilots were also asked whether or not and how they managed to explain the reported surprising automation behavior. Some pilots mentioned more than one source of information about the different automation surprises they had encountered. Of the 56 pilots answering this question, 22 pilots (39.3%) say that they never found an explanation for at least one of the reported surprises. In 24 cases (42.9%), the problem was explained by a more experienced crew member while 11 pilots (19.6%) figured out on their own what had happened. Consultation of the Aircraft Operating Manual (AOM) provided an explanation in six cases (10.7%).

In the last part of this question, pilots were asked for up to three detailed reports of automation surprises. Any report that contains too little information to allow for verification and for understanding the described episode was excluded from the data analysis as the anonymity of the survey did not provide an opportunity to gather additional information from pilots. In the end, 135 reports of automation surprises provided by 106 pilots were analyzed to identify categories of surprises that were of the same nature or seemed to have a common underlying cause.

The following paragraphs provide an overview of all surprises that were reported by at least five pilots (reports that were reported by less than five pilots are listed in Appendix B). The number of reports for each kind of surprise is indicated, and the basic nature of the problem is explained.

Failure to activate the approach 21 cases

Current automated systems have no way of knowing when the pilot is ready to begin the approach phase of flight. Pilots need to explicitly inform the automation about this transition by 'activating the approach'. This is achieved by pushing a line-select key next to the ACT APPR prompt which appears on the MCDU PERF DESCENT page once the descent phase of flight is active. By activating the approach, the pilot instructs the automation to slow down the aircraft to the manoeuvering speed for the current configuration once managed (i.e., automation-controlled) speed is activated. This allows the pilot to select successive approach configurations.

If the pilot forgets to activate the approach, the automation will not slow the airplane once managed speed is engaged by the pilot. Instead, it will increase thrust in order to return to its last active target speed which will be too high for the approach flight regime.

The large number of pilot reports related to surprising thrust increases resulting from the failure to activate the APPR may be explained in part by the fact that the coordination between pilots does not require explicit communication about transitions between flight phases. Pilots are therefore not used to and may forget the requirement to inform another agent about an event that is obvious to them. Another factor that is likely to contribute to the high frequency of the reported problem is a recent change in the A-320 software. Originally, the approach was automatically activated when the pilot selected flaps 1. In the current software version, however, the approach is not activated until the so-called deceleration point is overflown provided managed NAV is engaged. If the HDG SEL mode is active or if an early deceleration is required, the pilot needs to manually activate the APPR.

Loss of altitude/speed restrictions after entering a new approach or runway

20 cases

Experienced pilots on 'glass cockpit' aircraft try to spread their workload by pre-programming the automation for highly dynamic phases of flight. For example, pilots tend to enter all necessary information concerning an anticipated or ATC-assigned approach into the MCDU as early as possible. This includes the expected runway, STAR, specific ATC-assigned altitude and speed restrictions, and the MDA. Most of the twenty reported surprises refer to situations where pilots receive an amended clearance from ATC assigning a new runway after the data for the originally assigned approach and runway have already been entered by the pilot. Once the pilot changes the runway in the MCDU, all speed and altitude restrictions that he previously entered will be deleted by the automation even though they may still apply. The automation defaults to the assumption that a runway change results in a completely different approach.

'Indirect' mode transitions 14 cases

Another problem reported by fourteen pilots is the case of 'indirect' mode transitions where the automation changes its behavior without an explicit instruction by the pilot. Such unconfirmed transitions are likely to result in automation behavior that runs contrary to the pilot's intentions.

There are two major reasons for such indirect mode transitions on the A-320 -- in one case, the mode changes in response to the pilot entering a new FCU altitude when the airplane is about to capture the previously entered target altitude; in the other case, the transition occurs due to the airspeed exceeding a predefined limit. For example, if the pilot selects the Vertical Speed mode and enters a very high rate of climb which results in the airspeed decreasing below Vls + 5 kts (Vls refers to the lowest airspeed that can be selected by the pilot; it is 1,23 times the stalling speed of the selected landing configuration), the automation will revert to the Open Climb mode which allows the airplane to regain speed. Or if the airplane is within two hundred feet of a target altitude and the pilot selects a new FCU altitude, the vertical guidance automatically switches to the Vertical Speed mode and maintains the current vertical speed.

Exceeding 250 knots IAS below 10,000 ft 9 cases

These reports are related to violations of the requirement for pilots to fly their aircraft at or below an indicated airspeed of 250 kts below 10,000 ft MSL (Federal Aviation Regulation Paragraph 91.117 (a)). They involve a situation where, during a descent, the pilot selects an airspeed above 250 kts (e.g., in order to comply with an ATC clearance) and forgets to change this setting or fails to activate managed speed before he flies through 10,000 ft MSL. The automation will not "save the pilot" by either automatically reducing speed to 250 kts or by pointing out to the pilot that he needs to select a lower speed. It is not tailored to the official aviation rules of any particular country and therefore fails to realize and warn of or avoid their violation. Some pilots mention that they would expect the automation which seems highly proficient in other circumstances to detect the risk of a violation and to 'auto-slow' the airplane for them.

Autopilot disengages when intercepting the localizer
more than 20 nm outside from the airport — 7 cases

These reports refer to the situation where ATC clears the crew to intercept the localizer on an ILS approach when the aircraft is still more than 20 nm from the airport. While the automation is set up and engaged for the approach, the autopilot still disengages once the localizer is intercepted, solely due to a design decision that is not transparent or obvious to the pilot.

System priorities with respect to maintaining speed
and path in managed vertical navigation — 6 cases

These reports are related to a lack of understanding of the priorities that the automation adopts concerning flight path versus airspeed in managed vertical navigation. The automation tries to improve fuel efficiency and minimize thrust variations by compensating for any deviations from its target airspeed by allowing the airplane to deviate to some extent from the target altitude. This is not the way pilots manually fly the airplane, and therefore the automation behavior and its underlying tradeoff decisions surprise them.

Failure to immediately detect an FMGC failure 6 cases

In case of a single FMGC failure, a number of different problem indications may appear in various cockpit locations, depending on the circumstances of the failure. Provided the corresponding autopilot and flight director are engaged at the time of the failure, both systems automatically disengage. The flight director function is replaced by the other pilot's flight director which is indicated by a flashing box around the corresponding FD indication on the flight mode annunciations. After flashing 10 times, the box disappears and the FD1 indication changes to FD2 or vice versa.

If both pilots are in the same mode and range on their map display, they get a transient red message MAP NOT AVAILABLE on their map display. If their range and/or mode are different, a permanent message appears on the corresponding map display telling the pilot to "Select the offside range/mode". The current MCDU page is replaced by the MCDU subsystems page indicating the failure. And on the lower ECAM, a message appears informing the pilot that the corresponding autopilot and Cat III dual landing capabilities are inoperative.

The pilot reports in this category refer to situations where only some of all possible indications were provided. For example, in most cases, the corresponding autopilot and flight director were not engaged. In that case, a single FMGC failure does not involve any of the aural alerts associated with autopilot or flight director disconnect. This may have contributed to the reported failures to realize the problem immediately.

Unexpected speed targets during a Go-Around 5 cases

These five pilots report that they have been surprised by the airspeed targets that the automation tries to maintain in case of a Go-Around below 100 ft AGL with flight directors off. In the described cases, the automation either allowed the airspeed to increase beyond 250 kts below 10,000 ft, or the automation tried to maintain Vapp throughout the go-around. It is obvious from the reports that pilots had difficulties understanding the automation behavior even as they described the situation in the survey. Given the high degree of complexity of this situation and as the event was recreated in the scenario for the experimental study, a detailed description of the automation behavior and possible pilot reactions will be given in the corresponding section of this report.

Airspeed loss when leveling off in Open Descent 5 cases

The final group of reports refers to the situation where the aircraft is flown manually with at least one flight director on. In this case, if the pilot fails to follow the flight director bars while in Open Descent or Open Climb (with thrust being fixed at idle or at climb thrust), the aircraft will decelerate or accelerate until reaching Vls or Vmax at which point the ATHR will revert to SPD mode and V/S mode to stay within the speed envelope.

## 4.2.3 Information Gathering on the A-320

To better understand why breakdowns in mode awareness can occur, it seems important to examine pilots' approach to monitoring on advanced automated flight decks. Question 6a of the questionnaire asked pilots whether or not and in what ways the design of the A-320 PFD affects their technique of gathering flight-related information. 119 pilots responded to this question and provided detailed input on their new scanning techniques. 27 pilots explain that their scan has become a "one-instrument scan" with the PFD being the one instrument that provides all essential information. The same answer is implied in comments by another 22 pilots who state that their scan has simply become "smaller and quicker" on the A-320 in the sense that all basic flight parameters are shown on one screen (the PFD) instead of being spread out over various analog gauges.

Concerns with the presentation of flight-related data were voiced by seven pilots who think that the new display design (in particular the PFD tapes) requires that pilots focus on and read available information instead of being able to pick it up at a glance -- a strategy that was possible with conventional round-dial gauges. Another 21 pilots note that while the basic flight instrument scan has become smaller, other indications and displays such as the FMAs on the PFD, the ECAM displays, the MCDU, and the ND now need to be included in their scan, making it even wider than in conventionally equipped cockpits. Ten pilots comment that, initially, there is a risk of focusing exclusively on the flight director bars on the PFD.

Problems in verifying the status of the automation are mentioned by five pilots who tend to look at the FCU (e.g. showing commanded automation targets and modes) instead of monitoring the flight mode annunciations on the PFD (showing the actual automation configuration).

An important change in monitoring behavior on advanced automated flight decks is reported by fourteen pilots who explain that they no longer follow a basic instrument scan, i.e., a standard pattern of recurrently sampling a given set of basic flight parameters. Such a highly trained scanning pattern is used by pilots on conventional aircraft. It has the advantage of providing the pilot with guidance in terms of allocating his attention in an efficient way without missing critical items. In other words, it is a mentally economical approach to monitoring where the pilot is being told where to look next for relevant information.

In contrast, some pilots on the A-320 explain that they do not have a scan anymore. Instead, their information gathering is driven by specific questions that they ask themselves in particular task contexts. Their monitoring primarily serves to verify expected changes in the status and behavior of the automation and to answer uncertainties about the effects of input on aircraft behavior.

Note the fundamental difference between these two monitoring strategies. In the case of a standard scanning pattern, the pilot's attention allocation is externally guided while monitoring an advanced automated aircraft requires mental effort on the part of the pilot who has to determine on his own where to look next under varying task circumstances. The latter strategy seems to involve a higher risk of missing important information. Based on his expectations, the pilot only monitors part of all available data. Parameters that are not expected to change may be neglected for a long time. A standard instrument scan, on the other hand, serves to ensure that all relevant parameters concerning airplane behavior will be monitored at certain time intervals to make sure that no unexpected and perhaps undesirable changes occur.

The fundamental change in information gathering on advanced flight decks is likely to affect pilots' proficiency in basic instrument scanning -- a concern mentioned by ten pilots who expect or know from experience that it is difficult to go back to a conventional aircraft after flying the A-320 for some time.

### 4.2.4 Conclusion

The survey results indicate that mode errors and 'automation surprises' that have been observed on other less advanced automated aircraft also occur on the flight deck of the Airbus A-320. About 80% of all responding pilots report that they have been surprised by the automation at least once during line operations. These pilots provide detailed descriptions of the kinds of situations where the automation managed to surprise them. From their reports, different categories of surprises can be extracted that seem to share common underlying reasons.

The first category of automation surprises relates to situations where the *system fails to take an expected action*. For example, pilots report that they would expect the automation to "auto-slow" the airplane to 250 kts when approaching 10,000 ft MSL in order to comply with a corresponding aviation regulation. They are surprised that the FMGS does not even know about this regulation and therefore fails to support the pilot by preventing or at least pointing out the potential violation. Another example is pilots' expectation that the automation will always maintain a certain airspeed for them in case of a go-around when in fact, the automation fails to do so under some circumstances.

A second category of surprises involves situations where *the automation carries out an action that was not explicitly commanded by the pilot.* An example is the case where the automation deletes pilot-entered altitude or speed constraints for the arrival in response to a pilot-entered change of the expected runway. The automation makes a (false) assumption about the implications of the pilot's input and acts accordingly without verifying his intentions. Another example is situations where the automation initiates unexpected actions related to the prevention of unsafe or undesirable aircraft configurations. For instance, "indirect" mode transitions, i.e., mode transitions that are not commanded by the pilot but by the system designer, can occur in order to prevent excessive airspeeds.

Finally, a third category of automation surprises is related to *system failures that do not involve salient system indications to alert the pilot to the problem.* One such situation is the failure of a single FMGC as described by pilots in the survey.

All three categories of surprises are the result of a mismatch between the pilots' expectations and the actual system behavior. Either the pilot's expectations exceed the capabilities of the automation, or he fails to anticipate uncommanded side effects of his input to the automation, or he has no chance of forming any expectation at all as in the case of system failures.

Such mismatches between pilots' expectations and actual system behavior can create problems because of the monitoring strategies described by pilots in the survey. Pilots' allocation of attention within and across cockpit displays on advanced flight decks is guided by expectations. Therefore, a mismatch between anticipated and actual system behavior is likely to result in a failure to attend to relevant information at the right time. As a consequence, unexpected transitions in the status and behavior of the automation may go undetected, leading to mode errors of omission where the pilot errs by failing to intervene when necessary.

The results of the survey seem to indicate that such mode errors of omission are a dominant form of error on the flight deck of the A-320. Examples are the 20 pilot reports concerning a runway change leading to the unexpected and undetected deletion of altitude constraints or the 14 reports of failures to keep track of 'indirect' mode transitions. This trend towards mode errors of omission is disturbing because these errors are more difficult to detect than errors of commission which are more frequent in the context of less complex systems (Norman, 1981). In the case of errors of commission, the pilot can be expected to verify that his input has the desired effects, and he is therefore more likely to discover if his expectation is not satisfied. In contrast, mode errors of omission which occur in the absence of immediately preceding pilot instructions to the automation are more difficult to detect and recover from. The operator does not expect changes in automation behavior, and he is therefore less likely to pay attention to the relevant indications at the right time.

The data collection by means of the above survey was an important step in this line of research as it allows for the development of initial assumptions about the severity, nature, and underlying reasons for problems with pilot-automation interaction on the Airbus A-320. It is important to keep in mind, however, that the limitations associated with subjective data require that the suggested phenomena of interest be addressed in a more controlled study of pilot-automation interaction. In such a study, pilots can be confronted with instances of the reported problems to find out whether or not and how pilots manage to prevent or detect and recover from mode errors and automation surprises in the context of a flight scenario. It also helps explore whether some of the different categories or circumstances of automation surprises are more likely to create problems than others. The following section describes the experimental simulation study that was carried out as the final step in this line of research in order to examine these issues.

### 4.3 An Experimental Simulation Study of Mode Awareness and Pilot-Automation Coordination on the Airbus A-320

The final step in the reported line of research was an experimental simulation study of mode awareness and pilot-automation coordination on the flight deck of the A-320. This step was based on the results of the pilot survey which suggest that mode-related problems occur also on advanced automated aircraft. These problems seem to be symptoms of different forms of mismatches between expected and actual automation status and behavior. In many cases, they lead to mode errors of omission where the pilot fails to detect and (immediately) intervene with undesired automation behavior.

The experimental simulation study served to verify the results of the survey and to further analyze the nature and circumstances of as well as reasons for mode errors and 'automation surprises' in the context of advanced cockpit automation. Eighteen experienced A-320 pilots were asked to fly a 90-minute scenario on a full-mission A-320 simulator. The scenario for the study was designed to include a variety of tasks and events that represent instantiations of the problems suggested by the survey. These scenario elements are assumed to involve a high potential for surprises due to the design and behavior of the automation in combination with pilots' monitoring strategies on advanced flight decks. Behavioral data were collected throughout the flight to infer pilots' level of mode awareness and to examine how they cope with 'automation surprises'. These data were complemented by verbal data gathered during a debriefing to clarify observed behavior.

### 4.3.1 Experimental Scenario

The scenario for this simulation study was designed to address phenomena of interest that were suggested by the results of previous research on pilot-automation interaction (see Sarter and Woods, 1992, 1994, in press; Wiener, 1989) and by the input received from A-320 pilots in response to our survey. In particular, scenario tasks and events were designed and selected to serve as probes of pilots' mode awareness and of pilot-automation coordination -- two major areas of concern that seem to have played a role in recent incidents and accidents involving "'glass cockpit'" aircraft.

Such a phenomenon-driven approach to scenario design helps elicit specific behavior of interest instead of hoping for it to occur accidentally. Based on the results of the survey and of discussions with experienced line pilots, likely circumstances for the occurrence of problems with mode awareness and pilot-automation coordination had been identified, and in cooperation with an A-320 instructor, these phenomena of interest were translated into actual flight-related tasks and events that were combined and integrated to form a coherent and realistic scenario.

The major focus of this research was to explore the nature of and reasons for breakdowns in the coordination and communication between pilots and the automation which can result in so-called "automation surprises". The survey results suggest that 'automation surprises' can occur for a number of different reasons -- a) in cases where the automation fails to show expected behavior (e.g., failure to 'autoslow' to 250 kts below 10,000 ft), b) in cases where the automation takes an action that was not expected (e.g., elimination of altitude constraints when changing the runway in the MCDU), and c) in cases where a system failure occurs that can not be expected and that does not involve corresponding salient indications of the problem (e.g., FMGC failure).

The scenario for this simulation study was designed to include instances of these three categories of automation surprises in different circumstances to find out whether they in fact create problems for a significant number of A-320 pilots as suggested by the subjective data. The scenario also includes standard proficiency tasks to guard against the possibility that observed problems with the above specific probes merely reflect a generally low level of proficiency in handling the automation.

The scenario context is a 90-minute flight from Los Angeles to San Francisco which is rerouted back to Los Angeles due to a major power outage in Northern California. In the following sections, the scenario tasks and events that serve as probes of our phenomena of interest are described in detail. Several maps at the end of this section show the timing of scenario events along the route of flight.

Standard Proficiency Tasks

The following table provides a list of tasks that were included in the scenario to ensure that any observed difficulties with mode-related scenario events were not simply symptoms of a general lack of basic system knowledge and proficiency. Some tasks are not included in this list even though they would be regarded as standard proficiency tasks in the context of a pilot's checkride. The reason is that these tasks occur infrequently in actual line operations (e.g., flying an NDB approach) and can therefore be expected to present a challenge to pilots who have finished training some time ago.

Table 3. Standard Proficiency Tasks in the Scenario for the Simulation Study

| |
|---|
| Intercepting a Radial Outbound |
| Holding Present Position |
| Going Direct to a Waypoint |
| Programming an ILS Approach |
| Activating and Arming an Approach |

The first two tasks - the intercept and the hold - were set up in an atypical fashion to make them a little more difficult to handle. Pilots were given rather unusual but still realistic ATC clearances. This was done to explore whether pilots realize the need to deviate from their standard way of carrying out these tasks, and whether they know how to handle the atypical task requirements.

In the first case, pilots were asked to "intercept the San Marcus 320 degree radial outbound to the San Marcus 320 degree 50 DME fix". As suggested by Eldredge et al. (1991) based on their analysis of FMS-related ASRS reports, "the task of intercepting a VOR radial and flying the radial from the VOR is clearly one of the leaders in complexity" as opposed to the standard task of flying inbound to the radial.

The second clearance to hold "present position" used to be a rather rare instruction by ATC. Pilots in this study confirmed, however, that ATC personnel tend to make use of this option more frequently as they learn more about the capabilities of today's advanced automated cockpits which turn this clearance into an easy task.

## Probes of Mode Awareness and Pilot-Automation Coordination

The following sections describe those scenario events and tasks that were designed specifically to test pilots' awareness of the status and behavior of the automation and to study problems with the coordination between pilots and advanced cockpit technology. The three major classes of scenario tasks and events are a) situations that do not allow for the formation of expectation but require salient system indications in the interest of data-driven attention allocation, b) situations where the automation fails to carry out an action that is expected by the pilot, and c) situations where the automation takes a different or an additional action that was not anticipated. All of these situations seem to involve a high potential for surprise given that pilots describe their monitoring strategies as being expectation-driven. The following paragraphs describe the different instantiations of these situations in the scenario and the timing of tasks and events along the flight route.

A) Unpredictable Events

System failures are inherently unpredictable, i.e., they do not allow for the formation of expectations that could effectively guide attention to corresponding indications of the problem. Instead, salient indications of the problem need to be provided by the system to immediately attract the pilots' attention. Three different system failures are included in the scenario to test whether or not and how well the corresponding indications are capable of alerting the pilot to the problem. In the following paragraphs, these different failures are described in detail. The system failure associated with probably the least salient indications is presented first.

1) Loss of NDB signal during an NDB approach

This scenario event consists of the loss of the NDB ground signal which pilots are required to monitor during an NDB approach. In case of a loss of the signal, an immediate go-around is required. The only indications of a loss of the NDB ground signal are that a) the green ADF needle on the ND disappears, b) that the ADF identifier on the ND disappears, and c) that the ADF needle symbol next to the ADF ID disappears.

This failure does not trigger an aural alert, and there is also no positive indication of the problem appearing on any of the cockpit displays. In this scenario, a particularly difficult situation was created by failing the ground signal once the airplane was lined up with the ADF course. This results in the NDB needle being covered by the course line on the ND. In other words, the pilot can not see the needle or its disappearance for that matter. He only sees the head and tail (in the ARC mode of the HSI) or the tail only (in NAV mode) of the needle.

This particular set-up involves another aggravating factor, namely that the ground signal is failed very close to the outer marker where the pilot is busy focusing on the vertical flight path which he has to control manually using the V/S function on the FCU. He initiates the descent to the MDA at the outer marker.

2) Single FMGC time-out

A time-out of one of the two FMGCs (Flight Management and Guidance Computers) on the A-320 results in a so-called 'single-mode operation' where all peripheral devices (e.g. MCDUs, EFIS, RMPs) are driven by the remaining FMGC. Any entry on the intact MCDU is transferred to both MCDUs. A single FMGC failure is indicated to the pilot by various indications of the problem and its consequences in different locations in the cockpit. An amber message "OPP FMGC IN PROCESS" appears on the corresponding MCDU, and a transient red indication "MAP NOT AVAILABLE" is shown on the corresponding ND. A box around the FD indication on the corresponding PFD flashes 10 times, then disappears, and is followed by a change in indication from FD 1 to FD 2 or vice versa depending on which FMGS failed. An ECAM message appears stating that the corresponding AP is inoperative and that consequently LAND 3 FAIL OP is inoperative. If the two NDs are not in the same range and mode, a permanent amber indication "SELECT OFFSIDE RNG/MODE" is also displayed on the corresponding ND. No aural alerts are associated with this failure.

The large number of different indications in various locations would seem to make it easy for pilots to detect the problem. However, as indicated by the results of the survey, the lack of any aural alert provided the corresponding autopilot is not engaged and the possibility of other concurrent activities distracting pilots from monitoring their displays seem to reduce the likelihood of detection.

In this scenario, FMGC 2 was failed, i.e., the FMGC of the participating pilot in the right seat. To eliminate the aural alert associated with the disengagement of the corresponding autopilot, it was ensured that at the point of failing the computer, AP 1 (i.e., the Captain's autopilot) was in use. The instructor also ensured that both pilots were in the same range and mode on their NDs to prevent the permanent failure indication on the ND, another indication that would be almost impossible to miss. We were interested in finding out whether the MDCU, the PFD, and the ECAM messages were sufficient to catch the pilot's attention. In case the pilot did not detect either of those indications within one minute of their onset, the instructor was supposed to change the range on his map display to trigger a permanent indication of the problem on the participant's ND which was assumed to be sufficient to alert the pilot to the failure.

3) Glideslope transmitter failure during the final phase of a Cat II approach

The third and last case of a failure situation is the loss of the glideslope signal at approximately 400-600 ft AGL during a Cat II approach. This event requires an immediate go-around by the First Officer (the study participant). The first indication of a loss of glideslope signal is that the glideslope deviation index on the right-hand glideslope scale of the PFD disappears for 2-3 seconds. Then the glideslope scale and the flight director start flashing on the PFD. If the airplane descends below 200 ft AGL, the red AUTOLAND light illuminates on the glareshield, and an aural alert informs the pilot of a change in landing capability. This event was chosen as it involves a number of rather salient indications that can be expected to be successful in attracting the pilots' attention even under high-load, high-tempo circumstances.

B) The Violation of Expectations

Scenario events in this category involve situations where the automation fails to carry out an action that is expected by the pilot. Such a mismatch between expected and actual automation behavior can have various reasons. For example, it can be related to a misconception in the pilot's model of the automation, or it can result from an inconsistent automation design.

1) Need to (re-)activate the approach

On the Airbus A-320, the pilot needs to inform the automation about the transition to the approach phase. This step is necessary to ensure that the automation slows down the aircraft to allow the pilot to configure the airplane for landing. This coordination step is called "activating the approach" which is achieved manually by pushing the line select key next to the ACTIVATE APPR PHASE prompt on the DES PROG page of the MCDU and by pushing it once again to confirm the action. Another way of activating the approach is to wait until the DECELERATE pseudo-waypoint is overflown at which point the approach is automatically activated. If the pilot selects managed speed without the approach being activated, the automation increases rather than decreases thrust and speed to return to its last remembered target airspeed. The large number of pilot reports in our survey concerning the failure to activate the approach suggests that pilots expect the automation to know on its own when the approach starts and when to take corresponding actions.

To be able to re-create this situation, the instructor (PNF) was told not to activate the APPR until instructed to do so by the participating pilot. While in reality, the PNF should activate the approach, it is clear from the survey results that he sometimes fails to do so. The confederate set-up allowed us to test whether or not the participating pilot realizes that the automation has not yet been informed of the flight phase transition.

2) Maintaining 270 kts through 11,000 ft during the descent

In this situation, pilots are told to maintain an airspeed of 270 kts during their descent until reaching 11,000 ft. This clearance requires that the pilot manually selects an airspeed of 270 kts on the FCU. Upon reaching 11,000 ft, he needs to return to managed speed or to reduce the selected FCU airspeed to ensure compliance with FAR 91.117 that "no person may operate an aircraft below 10,000 ft MSL at an indicated airspeed of more than 250 kts". If he forgets to take action at 11,000 ft, the automation will continue to fly the aircraft at 270 kts even below 10,000 ft resulting in a violation.

This is an example of a situation where the automation fails to act like a proficient pilot and therefore creates a problem for the pilot who needs to remember that - in contrast to his fellow pilot - his machine counterpart has knowledge gaps and requires explicit commands. Given that the automation continuously receives information about the airplane's altitude and airspeed from its sensors, it is surprising that it is not designed to integrate this information and provide warnings to pilots when a violation is about to occur. However, this would require a software design that is tailored towards the specific rules and requirements of the country in which the aircraft is being operated.

3) Selecting a lateral guidance mode after takeoff or go-around

The A-320 defaults to flying runway track or go-around track following a takeoff or go-around. This can create problems as all other aircraft around it fly runway heading or any other ATC-assigned heading which means that in case of a strong crosswind with takeoffs from parallel runways there is a risk of two aircraft converging. To avoid this problem and to take positive control of the aircraft, pilots need to ask their co-pilot to either "select heading" or "activate managed NAV" shortly after takeoff or go-around initialization. There seems to be a high risk of forgetting this step as indicated by our survey results and by discussions with pilots, particularly in the infrequent case of a go-around which usually involves additional distracting factors that required the go-around in the first place. In our scenario, pilots were either told to fly runway heading after takeoff or they had to fly a published missed approach which was in the FMGC data-base.

## C) Unexpected Automation Behavior

### 1) Change of Runway - Loss of Altitude Constraints

In this case, pilots are given an initial ATC clearance for an ILS approach to runway 24 L (24 L refers to the left of two parallel runways - 24 L(eft) and 24 R(ight)) in connection with a number of altitude constraints for the arrival that are not in the FMGC data-base. Shortly after the entire clearance has been programmed into the MCDU, an amended clearance is issued to now expect an ILS approach to runway 24 R. When the pilot changes the runway identifier in the MCDU to 24 R, the automation also erases all previously entered altitude constraints without being instructed to do so by the pilot because it does not know whether they still apply. In contrast to a human pilot, the automation defaults to the assumption that the entire approach changes once the runway is changed. This creates a difficult situation for pilots who are used to fellow pilots knowing better and not requiring explicit coordination. To complicate matters, there is an exception to this rule. If the runway is changed after the first altitude-constrained waypoint has been overflown, the automation keeps and complies with all previously pilot-entered constraints.

In our scenario, the runway is changed before the first altitude constraint is overflown. As a result, all previously entered altitude constraints are lost. Pilots get an indication of this change on the MCDU display where the predicted altitude at the affected waypoints changes and the magenta star next to the altitude (which normally indicates that the altitude constraint will be made) disappears. Another indication of the problem is the disappearance of the altitude constraints which were depicted in magenta next to the corresponding waypoints on the ND.

In our scenario, the detection of the problem is made particularly difficult by the fact that the selected Sadde 5 arrival involves speed constraints that are in the FMGC database. These constraints are depicted next to the pilot-entered altitude constraints on the ND and remain in effect when the runway is changed. In other words, the disappearance of the magenta altitude constraints is difficult to detect as some magenta speed constraints still remain. Upon detection of the problem, the pilot has to re-enter the constraints into the flight plan via the MCDU in order to comply with the ATC clearance.

2) Expedite Climb

During climb-out, once the pilot has set up the automation to fly the airplane to an altitude of 12,000 ft with an intermediate level-off at Ventura at 10,000 ft, ATC asks the pilot to expedite his climb through 9,000 ft. At that point, the pilot can select from a number of modes to comply with this clearance. He needs to remember, however, that he needs to return to normal managed climb at 9,000 ft to make the altitude constraint at Ventura which is ignored in other climb modes.

This event not only serves to probe pilots' understanding and awareness of the automation behavior ("how the automation works") but it also gives us an opportunity to look at the different strategies pilots use to comply with a given clearance ("how to work the system"). In this particular case, the pilot can not only use the EXPEDITE mode but he has a second option of changing the speed target on the FCU to expedite his climb. By reducing the target speed, the pilot makes the aircraft climb at a steeper rate of climb. Upon reaching 9,000 ft, he only needs to return to the original speed setting to get back to the normal rate of climb. When using this technique, the aircraft will honor the 10,000ft altitude constraint at Ventura. A third option is to use the Vertical Speed (V/S) mode on the FCU. In this case, the pilot enters a higher vertical speed to make the airplane climb at a higher rate.

In case the pilot uses the EXPEDITE mode, he also needs to know that he can only disengage this mode by engaging another vertical mode -- pushing the corresponding FCU EXPEDITE button again does not have any effect.

3) Go-Around below 100 ft AGL with FDs off

This situation is a particularly challenging one as it involves a rare event in high-tempo highly dynamic circumstances. In all situations except this one, applying TOGA (Takeoff/Go-Around) power leads to arming of the autothrust system which means that it requires only a single pilot action for the autothrust system to be activated (i.e., pulling the thrust levers back to the MCT or CLB detent which are within the active ATHR range). In case of a Go-Around below 100 ft AGL, however, pushing the thrust levers to the TOGA position disconnects the ATHR. In that case, the pilot is left with manual throttles and has to control speed and altitude on his own.

In our scenario, during a visual approach backed up by ILS, pilots are told at 4-5 miles from the runway that they need to sidestep over to the parallel runway due to departing traffic. The ILS for that runway is reported out of service to ensure that pilots turn off the flight directors. Shortly after, they are forced to initiate a go-around at about 80 ft AGL due to landing traffic still on the runway. Autothrust does not arm, and pilots need to take steps to actively control the airplane's trajectory.

This situation is the most challenging one in terms of coordination between man and machine. As explained above, the automation reacts to pilot input - selection of TOGA power - in a way that drastically deviates from the way it reacts to the same input under all other circumstances -- the autothrust system disengages instead of being armed. The situation is highly dynamic and requires that the pilot monitors a lot of information and acts quickly to control the aircraft close to the ground. This is exactly the kind of situation in which the automation should support the pilot when, in fact, it completely deserts him and even gets in his way by behaving in an unpredictable way thus increasing the cognitive burden on the pilot-- a classical case of "clumsy" automation (see Wiener, 1989).

The following figures (Figure 5 through 7) illustrate the flight route for this study and the timing of tasks and events along this route.

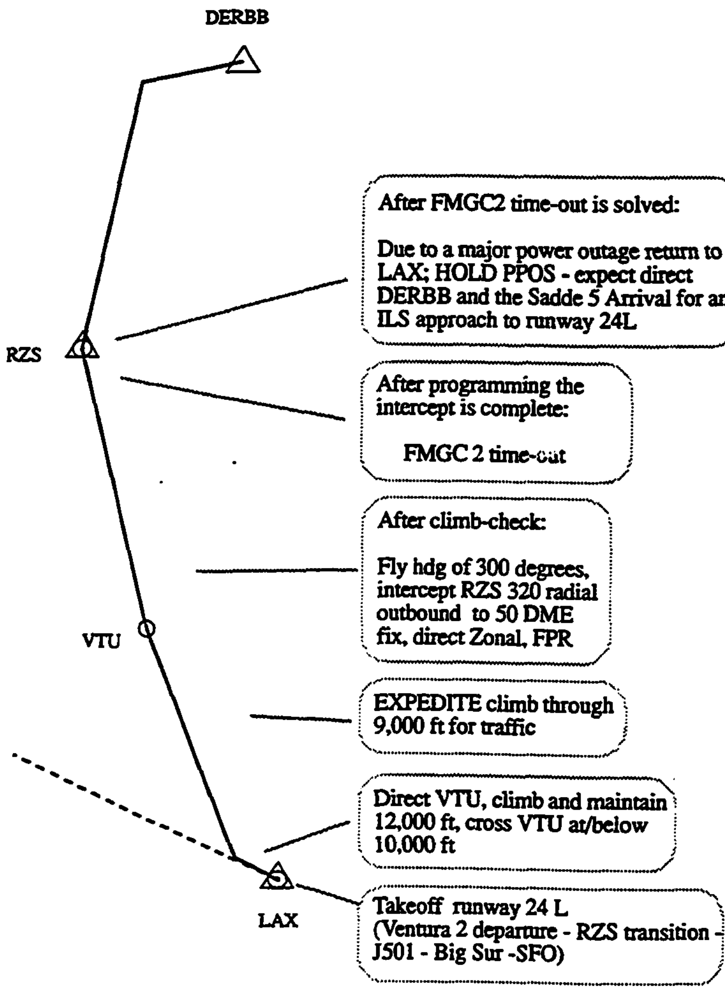



Figure 5. The Timing of Scenario Tasks and Events Along The Flight Route - From Takeoff to the Clearance Back to LAX

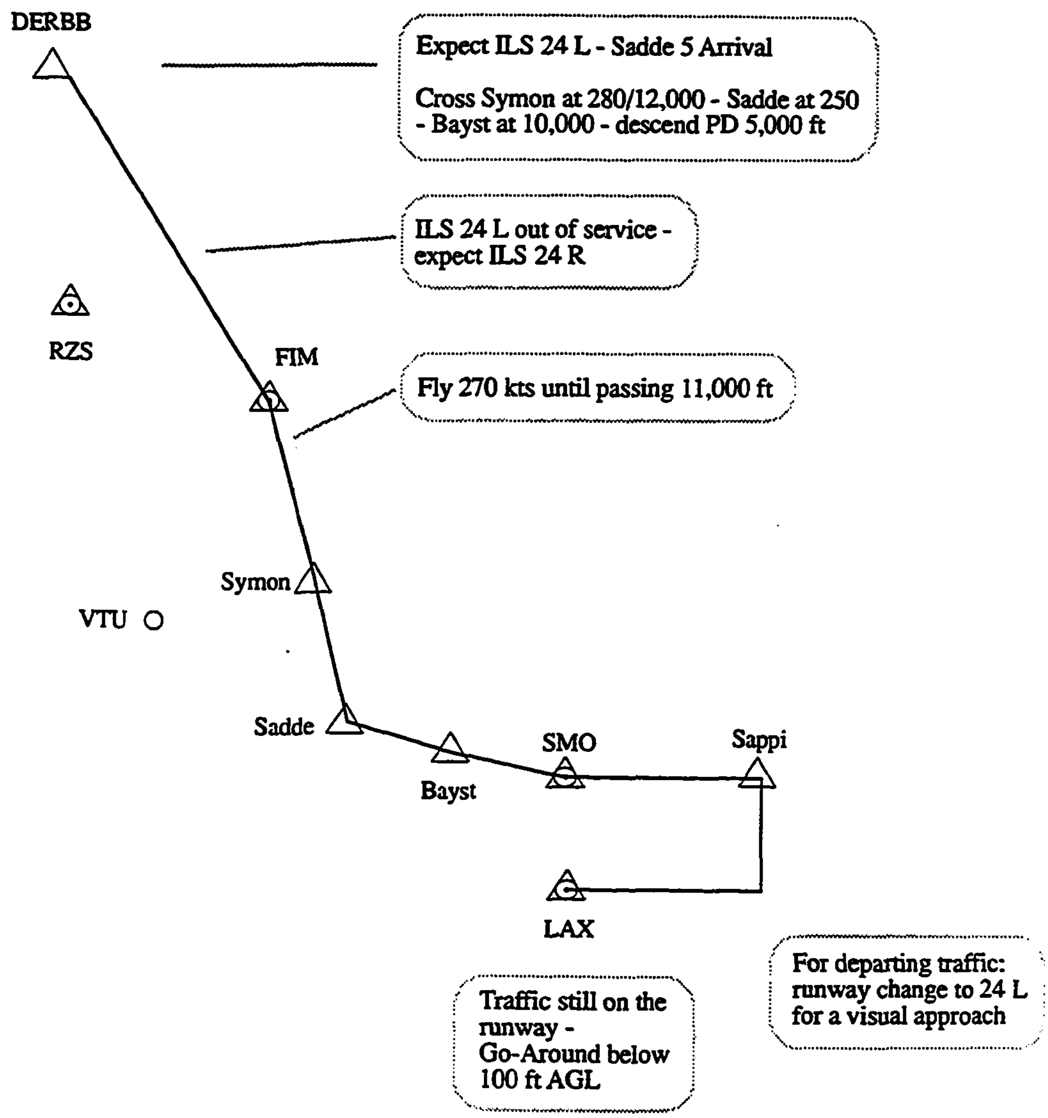
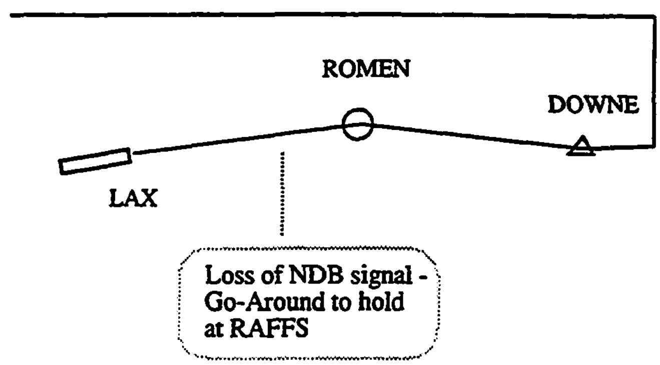



Figure 6. The Timing of Scenario Tasks and Events Along The Flight Route To The First Approach

## Second Approach

ILSs both out of service,
Radar Vectors for an NDB
approach to runway 24 R




## Third Approach

ILS Cat II approach for rwy 24 R

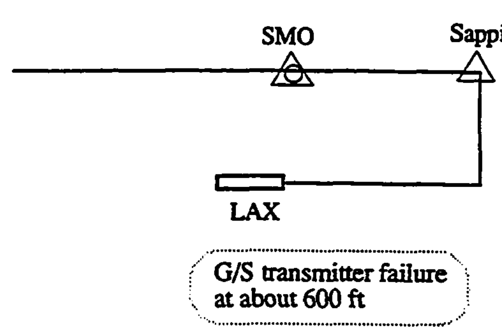



Figure 7. The Timing of Scenario Tasks and Events Along The Flight Route - The Second and Third Approach

## 4.3.2 Experimental Setting

An important step in planning an experimental simulation study is to identify an experimental environment that is representative of the target world, i.e., that includes those elements of the target world that are assumed to have an impact on the researcher's phenomena of interest. For example, important elements in the commercial aviation domain are a large number of concurrent tasks, the high-tempo event-driven nature of flight, and the large number of complex interacting systems in advanced automated cockpits.

For the purpose of this study, full-flight simulation seemed to be the most desirable approach as it provides pilots with an environment that is almost identical with a real cockpit. Recreating a system as complex as the one under consideration would be impossible due to financial and time constraints. While the complexity of the cockpit environment is also captured in part-task simulators, full-flight simulation has the additional advantage of providing the pilot with motion cues , outside view and auditory cues all of which are likely to have an impact on pilots' awareness of automation and airplane behavior which is conveyed not only via nominal indications on the cockpit displays but rather via a combination of these data with a variety of sensory inputs (such as engine sounds or pitch moments).

Accessibility of a full-flight simulation environment is often problematic because of the costs involved and because of the limited time available on most simulators which are used by airlines for training purposes. In this case, a major U.S. airline provided access to their full-flight Airbus A-320 simulator and was willing to cooperate with us on the project, in part because the results of our work were likely to yield results that would be useful for the evaluation and possible expansion of the airline's existing training program.

### 4.3.3 Study Participants

The participants in this study were 18 airline pilots who either responded to postings at the airline's training facility and pilot lounge or who were approached by the airline's training department. Participation was voluntary, and a nominal compensation was paid to pilots for their cooperation. The participating pilots were First Officers who had either less than or equal to 1,200 hrs of line experience on the A-320 (n=9) or more than 1,200 hrs of line experience on the airplane (n=9). 1,200 hrs translate into approximately 1.5 yrs of calendar time on the aircraft.

Table 4. Background and Flight Experience of Pilots Participating In The Experimental Simulation Study

| | <= 1,200 hrs of line experience on the A-320 (n=9) [mean (SD)] | > 1,200 hrs of line experience on the A-320 (n=9)[mean (SD)] |
|---|---|---|
| Age | 37.2 (2.1) yrs | 38.9 (3.4) yrs |
| Overall Flight Time | 7,111 (1,673) hrs | 8,933 (2,475) hrs |
| Hours on A-320 | 714 (312) hrs | 2,078 (295) hrs |
| Previous A/C | DC-9 1<br>B 727 3<br>B 747-200 1<br>DC-10 2<br>MD-80 1<br>B 757 1 | DC-9 4<br>B 727 4<br>MD-80 1 |
| Hours on A/C | 2,722 (1,666) hrs | 2,611 (1,381) hrs |
| Ever Glass | Yes 1 (B757)<br>No 7<br>MD-80 1 | Yes 1 (F-18)<br>No 7<br>MD-80 1 |

### 4.3.4 Procedure

Pilots were asked to fly a 90-minute scenario on an A-320 full-flight simulator. Simulated out-the-window view, motion and sound cues were generated and presented throughout the flight. The simulator is equipped with all cockpit instruments on the Airbus A-320 except for TCAS (Traffic Alert and Collision Avoidance System) and ACARS which are not critical for the phenomena under consideration.

Upon arriving at the simulator, pilots were given a short briefing on the context and purpose of the study, and they had a chance to ask for additional information before signing a consent form. They were informed about the role of the instructor who flew as Captain during the simulation. It was emphasized that the Captain would not deliberately create problems for the participating pilot through e.g. misentries. Pilots were informed that an observer [the author] would sit in the jumpseat behind the two pilots to collect data on the pilot's activities on-line, to operate the instructor console in the simulator, to change environmental settings such as weather conditions, and to simulate ATC.

The participants were asked to handle the automation just like in real line operations, and it was emphasized that speed of operation of the automated systems was not a concern in this study. The pilots were instructed to explicitly mention to us any observations of unexpected or strange system behavior. This requirement was explained to them by the need to detect in time any possible simulator problems. They were also told that any questions concerning the flight could either be discussed in flight with the Captain or during the debriefing after the flight.

Pilots were provided with the necessary flight paperwork. They were given as much time as necessary to familiarize themselves with the information contained in these documents. Subsequently, they were led to the simulator where they were asked to take the right seat in the cockpit. During the briefing, the instructor took care of the cockpit setup for the participant including entering all flight data into the MCDU and going through all checklists including the Before-Takeoff Check. The airplane was sitting at the end of the runway, ready for takeoff. Again, each pilot was given enough time to verify the data in the MCDU and to get comfortable in the cockpit.

As soon as the pilot indicated that he was ready for takeoff, the Captain asked for the takeoff clearance. The participating pilot was PF (Pilot-Flying) until shortly after level-off at their initial altitude. At that point, the Captain became PF so that the participating pilot had to take care of the automation-related input required to comply with amended clearances. Once the automation was set up for the first approach back into Los Angeles and after this approach had been briefed, the participating pilot was PF again for the remainder of the flight.

After completion of the flight, a debriefing served to ask additional questions concerning unexpected or unclear pilot behavior, about the indications that had attracted the pilot's attention to scenario events, and to discuss with pilots details of events they had either missed completely or handled in a problematic way. In that sense, the debriefing served as an instructional period as well. Pilots were also given an opportunity to ask questions about scenario events or tasks.

### 4.3.5 Data Collection

Both behavioral and verbal data on mode awareness and pilot-automation interaction were collected. The behavioral data were gathered during the simulator run; verbal data were extracted from the debriefing after the flight which was not interrupted for any questions.

As there is no direct measure of mode awareness, it was necessary to infer the pilot's level of awareness of the status and behavior of the automation from their performance on specially designed scenario tasks and events that place demands on attentional resources and can be hypothesized to require a sufficient state of awareness for good performance. All probes were designed to be operationally significant in the sense that they require observable pilot intervention once detected by the pilot.

Based on the experimental scenario, a canonical model of pilot behavior in response to these specific probes and events was built. This model lays out the set of plausible trajectories of pilot behavior, i.e., the various possible ways in which the pilot may respond to different probes. Developing such a model was the prerequisite for the design of a data collection sheet that would allow us to keep track of pilot behavior as it unfolds in the simulator. The data sheet also included space for additional notes concerning unexpected or unclear pilot behavior which was discussed with the pilot in the debriefing. During the experimental run, an observer [the author] was present to take notes and place checkmarks on the data collection sheet. The observer had to be knowledgeable about the entire range of possible FMGS operations in order to be able to keep track on-line not only of anticipated behavior but also of unexpected strategies or problems.

In the debriefing, pilots were asked about unclear or unexpected behavior. They were also asked what indications in the cockpit helped them detect the need for intervention that was created by some of the scenario events. Finally, they were given a chance to ask questions about the scenario and the study in general.

Both the observer and the instructor were present during the debriefing to ensure that both their own observations and possible questions by the pilot could be discussed. The debriefing took between 30 and 60 minutes to complete depending on the pilot's performance during the flight and depending on the pilot's interest in further discussions of issues related to the study.

## 4.3.6 Results

The data were first analyzed to identify those tasks and events that created problems for the majority of pilots, independent of their level of experience on the A-320. Subsequently, differences in the performance between the different groups of pilots were looked at in detail to determine whether increasing line experience leads to a reduction in the amount or nature of problems encountered by pilots. The strategies used by the different pilot groups in setting up the automation for handling scenario tasks were also compared.

### 4.3.6.1 Problematic Tasks and Events

#### Standard Proficiency Tasks

To ensure that observed problems related to our scenario probes of pilots' mode awareness and pilot-automation coordination are not merely the result of a general lack of proficiency in handling the automation, a set of standard proficiency tasks was included in the scenario. As all participants in this study were experienced airline pilots, no major difficulties with these tasks were anticipated. And, in fact, only few of the participants encountered any problems.

The following paragraphs describe the nature of the observed problems and the percentage of pilots affected by them.

## Intercepting a radial outbound

In real line operations, intercepts are usually flown *inbound* to some VOR . In our scenario, however, we increased the difficulty of the task by giving pilots the unusual clearance to intercept and track a radial *outbound to a fix* to see whether pilots understand that and how the setup of the intercept has to be changed. Six pilots (33.3%) had difficulties setting up the automation for the intercept due to this variation of the task -- two pilots were not sure how to create the fix by building the required place-bearing-distance waypoint; in three cases, pilots confused the sequence of the to- and from- waypoint for the intercept; and another two pilots forgot to delete their current from-waypoint to make Ventura the from-waypoint. In other words, while it was clear from pilots' comments that they knew in general how to build a standard intercept and that they understood the given clearance, they had problems with creating and sequencing the required waypoints to set up the automation for the unusual intercept. All pilots detected and recovered from their errors on their own based on the visualization of the created intercept on the map display.

While all pilots managed to build the intercept at some point, some of them did not take the first step recommended for this procedure, namely setting up raw data first to ensure that the intercept can be flown by the PF in case the programming requires too much time. Five pilots did not bring up raw data at all. Another four pilots brought up raw data first; but they displayed the raw data on their own map instead of showing it on the map of the PF who needed the information for guidance.

## Hold Present Position

Eight pilots (44.4%) had problems to comply with the ATC clearance to hold at their present position. Three pilots (15.2%) were trying to build the HOLD off their to-waypoint (MCDU - line 2L) rather than off the current from-waypoint (MCDU - line 1L). Two pilots (11.1%) entered the radial given to them by ATC under 'inbound course' in the HOLD menu. In two other cases, pilots failed to enter the specific HOLD parameters (distance of legs, direction of turn) requested by ATC . And one pilot (5.6%) failed to realize for some time that the inbound course did not have to be entered by him as it concurred with the default value.

In the first five cases, where a look at the map display provided immediate feedback about whether or not the hold had been built as intended, pilots detected and recovered from their mistakes on their own. In the latter five cases, however, where the pilots had to realize the problem based on a review of the data on the MCDU Hold page, pilots needed help from the instructor to realize that and how their input had to be modified.

## Activating the approach

In 14 cases (26% of all 54 approaches), the participating pilot forgot to remind the PNF to activate the approach. The scenario was set up in such a way that the PNF (played by the cooperating instructor) who usually takes care of activating the approach failed to do so in order to replicate the situation that had been reported in the survey as one of the most frequent sources of an automation surprise.

## Probes of Pilots' Mode Awareness and Pilot-Automation Coordination

The following paragraphs describe how the participating pilots handled tasks and events that were specifically designed and introduced to probe pilots' system and mode awareness and their coordination with their machine counterpart. Both the frequency and nature of problems will be presented for the overall group of participants.

### Unpredictable Events

#### Loss of NDB signal

During the NDB approach, the NDB ground signal was failed about two miles inside the outer marker. 11 pilots (61.1%) did not detect the loss of the signal and initiated a go-around due to low visibility only, as obvious from their actions and comments and confirmed by them in the debriefing. Two of these pilots indicated that they were not sure whether the NDB needle had disappeared but they failed to verify this suspicion. Of the six pilots who detected the problem, five of them realized that the NDB needle had disappeared while the sixth pilot noted that the ID was no longer displayed.

Interestingly, none of the pilots actually observed the occurrence of the event. Instead, they all noticed at some later point that some indication had disappeared from the screen. In the case of one pilot, this event could not be simulated due to a lack of time in the simulator.

FMGC failure

All 18 pilots realized the failure of FMGC 2 within one minute of onset. In the debriefing, ten pilots explained that the flashing box around the flight director annunciation on the PFD attracted their attention. Five pilots detected the problem based on the MCDU message related to the failure, and another three pilots were alerted by the transient 'MAP NOT AVAILABLE' indication on the map display.

Interestingly, not all pilots could immediately interpret the significance of the problem, and all pilots experienced problems in dealing with the problem as they could not find the appropriate sections which are distributed throughout the Cockpit Operating Manual.

Glide-Slope Transmitter Failure during Final Phase of Cat II Approach

Due to simulator problems, data with respect to this event could only be collected for thirteen pilots. All of these pilots immediately realized the loss of the glide-slope signal and initiated a go-around. In the debriefing, eleven pilots reported that their first indication of the problem was the flashing glide-slope scale on the PFD. Another two pilots first saw the flashing flight director bars on the PFD.

## "Surprising" Automation Behavior

### EXPEDITE Climb

During climb-out, pilots were cleared to climb and maintain 12,000 ft and to cross Ventura at or below 10,000 ft. Upon reaching approximately 4,000 ft, they were given the instruction to expedite their climb through 9,000 ft. Pilots had several automation options to choose from to comply with this clearance.

Eleven pilots used the EXPEDITE button on the FCU to engage the EXPEDITE mode. All of these pilots knew how to disengage the EXPEDITE mode again upon reaching 9,000 ft. Five pilots selected a lower airspeed on the FCU to make the airplane climb at a higher rate of climb. And the remaining two pilots used the vertical speed mode and dialed in a higher than normal rate of climb on the FCU.

In the debriefing, seven pilots were asked why they did not use the EXPEDITE mode which was designed for this type of situation. They responded that they did not like the fact that the automation would drastically increase the pitch angle and slow the aircraft all the way to green dot speed. In addition, pilots knew about and disliked the fact that the EXPEDITE mode would not comply with any preprogrammed constraints.

Only 11 pilots (61.1%) complied with the altitude constraint at Ventura. The other seven pilots remembered to resume 'normal climb' at about 9,000 ft but they selected the so-called "Open Descent" mode (instead of 'managed vertical navigation') which does not honor constraints programmed into the MCDU. Four pilots showed clear signs of anticipating the need for resuming "normal" climb as they reached for the ALT knob long before reaching 9,000 ft.

It is interesting to note that the constraint indications on the ND do not reflect this situation. On the ND, the 10,000 ft constraint at Ventura is indicated in magenta as "-10000" independent of whether or not EXPEDITE is active, i.e., independent of whether or not the airplane will actually level off at that altitude.

Change of Runway

In this situation, pilots have programmed the anticipated ILS approach to LAX runway 24 L in the MCDU including a number of ATC altitude constraints for their arrival. ATC then informs the pilot that the ILS for runway 24 L just failed and that they can now expect an approach to runway 24 R. When the pilot changes the runway in the MCDU in response to this new information, his action leads not only to the desired runway change but also to the loss of all altitude constraints he entered for the originally planned approach.

Ten pilots realized right away or even anticipated the loss of constraints. Another four pilots detected the problem when they were given the clearance to maintain 270 kts until reaching 11,000 ft. They selected 270 kts on the FCU and then looked at the map display where they realized that the magenta indications for the programmed altitude constraints were no longer shown next to the corresponding waypoints.

Of these fourteen pilots, only twelve recovered from the problem in time to still make the constraints by re-entering them. One pilot made the constraints even though he did not detect the problem -- he happened to fly a descent profile that led to inadvertent compliance. This latter case is a good example of the loose coupling between process and outcome in the context of highly complex systems (see Woods et al., in press)

Go-Around and Published Hold

The scenario involves one situation where pilots have to fly a published go-around to hold at Raffs intersection. Once a Go-Around is initiated, the automation defaults to the so-called "Go-Around Track" mode for lateral guidance. In this mode, the airplane flies runway track until the pilot intervenes.

In four cases, pilots forgot to activate managed navigation which was necessary to make the airplane fly to Raffs and enter the holding pattern. Five pilots activated managed navigation rather late in the go-around. They were 2-3 miles from the holding fix when they realized based on indications on the map display that the airplane was still in the runway track mode. Two pilots were late activating managed NAV because when they first reached for the FCU heading knob, they saw the dashes in the heading window which usually indicate that managed NAV is active. This made them hesitate with pushing the knob but after reviewing the indications on the PFD, they finally activated managed NAV.

Go-Around below 100 ft AGL

One possible way of handling this situation is to set the thrust levers to TOGA, to rotate to 15 degrees pitch up, to ask for flaps up, and to maintain a safe airspeed by using the throttles like manual throttles. When reaching the acceleration altitude, a target speed such as green dot should be selected on the FCU, pitch should be reduced to about 12 degrees, thrust levers need to be put to the CLB detent and ATHR can be activated. Flight directors can be turned on, and appropriate automation modes can be selected.

If the pilot does not realize that the autothrust system has disengaged, he may experience a number of problems. First, airspeed rapidly increases as the thrust levers are in manual mode and set to full power. The pilot will have to quickly configure the airplane to avoid overspeeding the flaps. After bringing up the flaps, the airplane will continue to increase its speed. If the pilot now realizes that ATHR is not engaged, he may choose to activate ATHR by pushing the ATHR button on the FCU. This action, however, if not preceded by selecting a target speed on the FCU, will result in yet another problem. The automation will revert to the last target speed it remembers, namely Vapp. In other words, initially the airplane may fly at a rapidly increasing airspeed; once ATHR is selected, the power will come back to idle to slow the airplane to a speed of about 135 to 140 kts. The solution is to select a target speed on the FCU which will allow the pilot to safely revert to using ATHR again.

The pilot gets one indication that ATHR is not armed from column five of the Flight Mode Annunciations on the PFD. The indication "ATHR" which usually appears in blue (armed condition) in that location is not shown. In fact, in the initial phase of this Go-Around, all FMAs will be blank as the pilot turned off the FDs and the AP to fly a visual approach to runway 24 L. Another possible cue of the problem could be the absence of the flashing CLB indication at thrust acceleration altitude which appears if autothrust is armed to remind the pilot of returning the thrust levers to the CLB detent to activate autothrust. With some experience on the airplane, pilots can be expected to anticipate this prompt and may be puzzled if it does not appear. On the FCU, the ATHR button is not illuminated which is yet another cue that ATHR is not engaged. Once the pilot activates ATHR without selecting an FCU speed first, the Vapp airspeed value appears as the target speed in the FCU speed window, and it is also shown in blue digits below the airspeed tape. In terms of aircraft behavior, the pilot will immediately realize the continuous and rapid increase in airspeed which can proceed all the way up to Vmo. Conversely, after engaging autothrust without entering a target airspeed, he will observe an unexpected change to idle power and a rapid decrease in speed far below green dot towards Vapp.

Only one pilot was able to handle the Go-Around below 100 ft AGL without any problems. He elected to stay in fully manual control until level-off at acceleration altitude and then re-engaged individual subsystems of the automation one after the other.

All other pilots were trying to figure out why the automation did not behave as expected, and they tried to get guidance from the automation as soon and as much as possible. For example, seven pilots first called for the flight directors to be turned on after initiating the go-around even though the automation was not set up for any guidance. Another seven pilots (38.9%) activated autothrust before selecting a target speed which resulted in Vapp becoming the airspeed target.

The fact that most pilots hesitated to take manual control of the aircraft instead of trying to understand what the automation was doing resulted in problems, some of which were severe enough to result in violations. For example, six pilots (33.4%) exceeded 250 kts IAS below an altitude of 10,000 ft. Two pilots allowed the airspeed to increase until almost reaching Vmax. Another two pilots (11.1%) oversped their flaps during the Go-Around. Three pilots allowed the airspeed to increase all the way to Vmo before taking an action.

During the debriefing, all pilots explained that they had not expected the autothrust to disengage when applying full power. They were surprised by the increasing airspeed, and could not explain to themselves what was going on. Pilots emphasized that they were watching airspeed trends and their altitude instead of looking at the flight mode annunciations to find out about the actual status of the automation. As one pilot put it, they experienced "a moment of denial" when they could not believe that the automation would not fly them out of this situation. All pilots agree that autothrust should arm in this situation, and no pilot felt that Vapp was an appropriate target speed for this situation. Two pilots suggest that green dot should be the airspeed target while a third pilot felt that 250 kts would be appropriate.

All but three pilots were asked how they would try to explain the current design, and a number of possible reasons were proposed. One pilot felt that the design was simply the result of an oversight by Airbus. Two pilots suggested that the automation assumes the intention of landing once the airplane descends below 400 ft AGL. One pilots thought that the Vapp target speed may be based on the possibility of an engine-out condition. Finally, one pilot thought that autothrust was not available in this situation as manual throttle operation makes the engines spool up faster, and another pilot argued along the same line that the design was meant to get the airplane away from the ground as soon as possible. Nine pilots could not see any good reason at all for the current design.

To determine whether most of the numerous above described problems were encountered only by less experienced pilots, the following sections provide a more detailed analysis and comparison of two pilot groups at different levels of line experience on the A-320.

#### 4.3.6.2 Differences Between Pilots at Different Levels of Experience with the A-320 Automation

Previous research suggests that the number of "automation surprises" for pilots on 'glass cockpit' aircraft decreases only with considerable line experience (see Wiener, 1989; Sarter and Woods, 1992). For example, pilots have indicated that they start feeling comfortable with using the automation only after about 1,200 hrs of line experience (e.g., Uchtdorf and Heldt, 1989; Sarter and Woods, 1992).

To examine whether differences between more versus less experienced pilots can be found in this study, the overall group of participating pilots in this study was split into two groups -- one group with less or equal to 1,200 hrs of line experience which translates into about 1.5 yrs on the airplane (Group I - n=9) and one group with more than 1,200 hrs of experience (Group II - n=9). The biographical and flight background data for these two groups were presented in section 4.3.3.

The following paragraphs compare the performance and strategies of these two groups with respect to those scenario tasks and events that focus on system awareness and pilot-automation coordination.

## System Failures

### FMGC time-out

No difference was found between the two different groups of pilots with respect to the detection and handling of the single FMGC failure. All pilots detected the problem within one minute of its onset, and they all had difficulties finding the corresponding procedure for handling the problem which is addressed in various different sections of the Cockpit Operating Manual (COM).

### Loss of ground signal during NDB Approach

In each group, only three pilots realized the loss of the NDB signal. In the group of more experienced pilots, a fourth pilot made remarks indicating that he suspected that he had lost the signal but he failed to verify this concern. Six pilots in each group initiated a go-around due to low visibility only.

During the debriefing, all of the less experienced pilots reported that they had realized the problem based on the disappearance of the ADF needle on the map display. In the second group, two pilots had seen the ADF needle disappear, and one pilot first realized that the ADF identifier was no longer displayed on the map.

As pointed out in the section on results for the overall group of participating pilots, the NDB approach can be flown using different automation modes and system setups. As these options may affect the likelihood of error detection, it seems important to look for differences in these settings between a) the two different groups of pilots at different levels of experience and b) between those pilots who detected the problem versus those who failed to do so. The following table shows the results of these two comparisons.

Table 5. Comparison of the Automation Set-Up For an NDB Approach Adopted By Pilots At Different Levels of Experience with the A-320 Automation

| | Group I (n=9) | Group II (n=8) |
|---|---|---|
| Lateral Navigation | | |
| managed | 7 | 8 |
| selected | 2 | 0 |
| Map Mode | | |
| ARC | 3 | 5 |
| NAV | 6 | 3 |
| Audio Setting | | |
| on | 2 | 1 |
| off | 7 | 7 |

No significant difference was found with respect to whether pilots make use of available auditory feedback by monitoring the NDB frequency. The majority of pilots in both groups flies the NDB approach in managed lateral navigation, thus assigning the task of lateral guidance by tracking the NDB signal to the automation. Only two pilots in the less experienced group flew the approach using selected heading which requires that the pilot continuously monitors for deviations from the desired course in addition to controlling the vertical trajectory of the airplane using the V/S mode. The difference observed between the different pilot groups with respect to their preferred map mode in this task context is also not significant.

Another important question is whether there were significant differences in the strategies and set-up used by pilots who detect the NDB loss versus those who initiate a Go-Around due to low visibility only. The following table provides an overview of those data.

Table 6. Comparison of Automation Set-Up For an NDB Approach By Pilots Who Did/Did Not Detect the Loss of the NDB signal

| | Problem Realized (n=6) | Problem Not Realized (n=11) |
|---|---|---|
| Lateral Navigation | | |
| managed | 66.7% | 100 % |
| selected | 33.3 % | 0 % |
| Map Mode | | |
| ARC | 50 % | 81.8 % |
| Rose NAV | 50 % | 18.2 % |
| Audio | | |
| on | 0 % | 27.3 % |
| off | 100 % | 72.6 % |

Although the comparison does not yield significant differences, there seem to be different trends in the set-up of the automation in the two pilot groups. One third of the pilots detecting the NDB signal loss were flying the approach in selected navigation. On the other hand, all the pilots who did not detect the problem were flying in managed navigation. This result indicates that while involvement in the control of both lateral and vertical navigation may be more taxing, it also increases the likelihood of realizing the loss of guidance.

Another interesting finding is related to the question whether listening to the audio signal of the NDB frequency increases the likelihood of detecting the signal loss. Surprisingly, none of the pilots who did in fact realize the problem had turned on the audio equipment. On the other hand, three pilots who listened to the auditory signal still failed to realize that the signal failed.

## "Surprising" Automation Behavior

### EXPEDITE Climb

The two pilot groups show no significant differences between their choice of automation modes to comply with the request to expedite their climb as shown by the following table:

Table 7. Comparison of Automation Modes Used to Expedite Climb By Pilots At Different Levels of Experience with the A-320 Automation

| | Group I (<= 1,200 hrs) | Group II (> 1,200 hrs) |
|---|---|---|
| EXPEDITE mode | 5 | 6 |
| Lower FCU Speed | 3 | 2 |
| Vertical Speed mode | 1 | 1 |

There is also no significant difference between the two groups with respect to their compliance with the 10,000 ft altitude restriction at Ventura. Five of the less experienced versus six of the more experienced pilots complied with the constraint.

Go-Around To Hold at Raffs

Once the pilot initiates a go-around, the automation defaults to the Go-Around Track mode, i.e., the airplane is flying runway track until the pilot intervenes. The two groups of pilots differ with respect to whether or not and when they activate managed navigation as required in order to make the airplane fly to the Hold fix.

While three of the less experienced pilots (33.3%) completely forget to activate managed navigation, four of the more experienced pilots initially forget to do so but recover shortly before reaching the Hold fix.

Go-Around below 100 ft AGL

The two pilot groups seem to differ with respect to how they handle the Go-Around situation below 100 ft AGL with flight directors off. Two pilots in the less experienced group oversped the flaps as they reacted too slowly to the rapidly increasing airspeed. None of the pilots in the more experienced group encountered this problem. However, five of these pilots - in contrast to only 2 pilots in the less experienced group - selected autothrust before selecting a target speed thus creating a situation where the automation slows the aircraft to Vapp, its last target speed before its disconnect. Six pilots in the less experienced group exceeded 250 kts below 10,000 ft.

### Activating the Approach

In the less experienced pilot group, pilots forgot to activate the APPR in 10 cases while only 4 such cases were observed in the group of more experienced pilots.

### New Destination

Six of the less experienced pilots did not know how to enter a new destination into their flight plan when they were told to return to Los Angeles. Only two of the more experienced pilots encountered problems with this task. In most cases, pilots were trying to do a lateral revision off the current destination which would bring up the arrivals for that destination. Instead, the correct procedure is to do a lateral revision off any other waypoint except pseudo-waypoints and discontinuities which were used unsuccessfully by some other pilots. Most pilots mentioned during the flight or the debriefing that they had never used this function during line operations.

Interestingly, a change in destination automatically leads to a recomputation of the cruise airspeed target by the automation. This effect was accidentally detected during one of the experimental sessions; clearly none of the pilots had ever heard about it.

## 4.3.7 Discussion

The survey and the experimental simulation study provide converging evidence showing that recent developments in the design and capabilities of cockpit automation have not reduced or eliminated 'automation surprises' and mode errors. These problems with pilot-automation interaction also exist on the much more advanced flight deck of the Airbus A-320. However, the nature of and the underlying reasons for these symptoms of breakdowns in the communication and coordination between man and machine appear to have changed to some extent, possibly reflecting the increased autonomy and authority of the automation as well as the different feedback and control design on this airplane.

A fairly large number of pilots revealed a lack of system awareness in the context of the following scenario events and probes: a) the NDB failure, b) the runway change, c) the expedited climb, and d) the go-around situation below 100 ft AGL. Eleven pilots never realized the loss of the NDB signal which normally provides lateral guidance to the automation. One possible explanation may be that it is impossible for pilots to form expectations of system failures. Their ability to detect failures is therefore largely determined by the interface design which needs to attract their attention to the relevant indications at the right time (Billings, 1991). The "cueing by absence" approach which has been shown to be ineffective in previous studies (Sarter and Woods, 1994) is also not successful in alerting pilots in this situation.

The other system failures in the scenario - the glideslope transmitter failure and the single FMGC failure - involve the same fundamental problem for the pilot. It is impossible to anticipate them. However, they were detected by all pilots in time to take an appropriate action. This may be explained by the positive fairly salient indications that are associated with these problems.

Interestingly, those pilots who realized the loss of the NDB signal did so some time after the signal had actually been failed. This again supports the notion that the disappearance of an indication does not capture attention. Instead, the absence of an indication is only detected once a pilot decides to attend to the indication and realizes that it is missing. Similarly, the first indication of the G/S transmitter failure - the disappearance of the G/S scale and diamond - was missed by all pilots. In contrast, all participants immediately realized the problem once the G/S scale and the flight director bars on the PFD started flashing.

Further problems with mode awareness were observed in the context of those scenario events that made it difficult but not impossible to anticipate system behavior. In case of the go-around below 100 ft AGL, all pilots failed to anticipate and realize that the autothrust system did not arm when they selected TOGA power. In this case, the pilots had an expectation of system behavior in response to their input. As mentioned by pilots in the debriefing, they all expected the autothrust system to arm because it does so in all other cases where TOGA power is applied. In that sense, the problem seems to be incoherent system behavior in a high-tempo highly dynamic phase of flight where pilots may have to rely on their automated systems to act as expected.

In this situation, most pilots either hesitated very long before taking any action or they focused on getting the automation set up for guidance. In the first case, pilots' behavior may be explained by what one pilot called "a moment of denial" in the debriefing. He said that he could simply not believe that the automation would desert him and not manage thrust and speed for him.

In the second case, pilots tried to re-engage the flight directors and to set up the automation to provide them with lateral and vertical guidance. This behavior suggests that pilots have come to rely on the automation to an extent that they are willing to focus on the automation at low altitude in an unclear situation instead of immediately taking manual control of the aircraft.

The NDB signal loss and the go-around below 100 ft AGL are rare events that pilots may have never encountered in real line operations. All they could rely on was their model of the system that they develop based on their interaction with the automation in normal circumstances. The other problematic situations - the runway change and the expedited climb - are more likely to occur, and some of the participating pilots may have learned about the particular system behavior from experience. Not surprisingly, fewer pilots experienced a problem in these situations. Still, the overall number of 13 altitude violations is an alarming result. Six pilots failed to detect and recover in time from the loss of previously entered altitude constraints as a consequence of the runway change in the MCDU. Seven pilots violated an assigned altitude when they reverted to an inappropriate mode from the EXPEDITE CLIMB mode.

The problem in these cases seems to be that the pilot provides an instruction to the automation without realizing the additional unintended implications of his input. Given that he is not aware of or does not consider these implications, he fails to look for and detect the corresponding indications of system behavior. In case of the runway change, the pilot never tells the automation to delete any altitude constraints. The automation does so on its own based on instructions by its designer. When leaving the EXPEDITE mode, some pilots revert to the OPEN CLIMB mode which does not honor any altitude constraints in the MCDU. In this case, pilots get confused as they have to select from at least five different climb modes. An additional contributing factor may be that pilots only had 1,000 ft to go when they had to change modes. In other words, they had to take action fairly quickly which may have added to the confusion about the appropriate mode.

Note that none of the pilots in this study had any difficulties with disengaging the EXPEDITE mode. In the survey, some pilots reported problems with this task as they had tried to push the corresponding FCU EXPEDITE button again instead of activating a different vertical mode. In other words, they committed errors of commission by taking an action that was inappropriate given the current status of the system.

With respect to the comparison between pilots at different levels of experience with the A-320 automation, hardly any differences were observed. The only trend seems to be that the more experienced pilots are more likely to detect and recover from an error. An example is the go-around situation where the automation defaults to the go-around track mode. Some of the less experienced pilots completely forget to activate managed NAV. The more experienced pilots initially make the same mistake but they detect the problem in time before reaching the holding fix. In the go-around situation below 100 ft AGL, the more experienced pilots are faster in taking manual control of the aircraft to comply with target speed and altitude.

Another interesting result of the simulator study is that - as demonstrated in previous studies (e.g. Sarter and Woods, 1994) - standard proficiency tasks do not create problems for experienced 'glass cockpit' pilots unless they involve some unusual aspect that requires deviations from the normal procedure for carrying out the task. For example, the intercept creates problems for some pilots only because of the unusual clearance asking pilots to fly outbound from rather than inbound to a VOR. This clearance requires that pilots build a fix outbound on the radial as the automation always flies towards never away from a waypoint. In other words, pilots need to create a To-Waypoint and then properly sequence the To- and From-Waypoints in the Flight Plan. In this study, pilots had difficulties only with respect to these unusual aspects of the task. In case of the requirement to hold present position (instead of 'at a fix on a certain radial'), the result looks similar. Pilots show that they know how to build a Hold but they have difficulties figuring out how to do so at their current position.

In all cases where a visualization of pilot input is provided on the map display, pilots detect erroneous commands to the automation based on the mismatch between expected and actual outcome, and they have no difficulties with revising their input. In contrast, problems that had to be detected based on the alphanumeric data in the MCDU were missed by several pilots. They had to be pointed out to the participant by the cooperating instructor. Once pilots were told about the problem, they had no difficulties to recover.

This may explain why the map display is a favorite feature of pilots on 'glass cockpit' aircraft as shown by Wiener (1989) who asked B-757 pilots which features they would miss most if they had to leave the B-757 for an older model aircraft. 69 of the 133 pilots who were asked this question mentioned elements of or the entire HSI or map display as one of their favorite features.

The results concerning pilot performance with respect to the standard proficiency tasks raise a concern. They may indicate that pilots carry out tasks based on 'recipes' and are therefore likely to encounter problems once novel circumstances require a deviation from those standard procedures. In other words, once knowledge-based behavior is required, pilots may have difficulties which can be explained in part by current approaches to training that do not emphasize the need for a model of the functional structure of the system. Such a model would allow pilots to derive appropriate actions for novel situations.

In summary, the results indicate that mode errors do occur on the flight deck of the Airbus A-320. They result in 'automation surprises' and are symptoms of a failure to create a cooperative human-machine ensemble through design and training. It is interesting to note that the majority of observed problems with mode awareness in this study result in mode errors of omission where the pilot fails to realize that the automation has taken an undesired action and, consequently, fails to intervene to recover. In case of the runway change, for example, some pilots fail to realize or realize too late that the automation has deleted all previously entered altitude constraints. During the go-around to a published hold, some participants fail to realize that the automation defaults to the Go-Around Track mode instead of flying towards the holding fix in managed NAV. During the Go-Around below 100 ft AGL, most pilots do not catch the fact that the autothrust system does not arm. And in 26% of all approaches, pilots fail to realize that the approach has not been activated. Errors of commission, while possible given the scenario tasks and events in this study (e.g., the need to disengage the EXPEDITE mode), were hardly observed at all.

The large number of mode errors of omission in this study may reflect the increased autonomy of the automation on the A-320. The automation can take action or change its behavior without immediately preceding pilot input. In some situations, it surprises the pilot by carrying out more than the explicitly commanded action based on unverified assumptions about the pilot's intentions. For the pilot it is difficult to form expectations of such uncommanded or externally triggered behavior. According to pilots' comments in the survey, these expectations of system behavior are critical, however, as they provide guidance for the pilot's attention allocation within and across displays. Without expectations, he may therefore miss indications of transitions in system behavior and fail to intervene when necessary. Previous research looking at less autonomous cockpit automation (see Sarter and Woods, 1992 on the B-737-300/400) found problems to be related more often to the operation of the system and to errors of commission where a lack of system awareness leads to actions that are inappropriate for the actual status of the system. .

# CHAPTER V

## PROPERTIES OF ADVANCED AUTOMATION AND THEIR CONTRIBUTION TO BREAKDOWNS IN MODE AWARENESS

*"Errors are not some mysterious product of the fallibility or unpredictability of people; rather, errors are regular and predictable consequences of a variety of factors." (Woods et al., in press)*

The results of this research suggest that new design features and capabilities of advanced (flight deck) automation increase the opportunity for a new kind of error -- mode errors of omission. Mode errors are symptoms of a lack of mode awareness which can be observed in the context of both early and more recent generations of automated cockpit systems. But while a lack of mode awareness on earlier automated flight decks tends to result in errors of commission (Sarter and Woods, 1994), it takes the form of errors of omission on highly advanced aircraft. In other words, mode errors on less advanced aircraft tend to be related to a misassessment of the automation status and behavior. Based on this misassessment, the pilot takes an action that is not appropriate to achieve his objectives given the actual automation configuration -- the classic form of mode error (Norman, 1981). Mode errors on advanced technology aircraft are more often associated with the pilot's failure to detect and intervene with undesired system behavior that was not explicitly commanded by him -- an error of omission.

We can think of errors as predictable consequences of the interaction among "three mutually constrained factors: the world to be acted on, the agent or agents who act on the world, and the external representations through which the agent experiences that world" (Woods and Roth, 1988). In other words, the interaction of factors related to the design of a system, to the abilities and limitations of the system user, and to the circumstances under which the system is being used needs to be examined in order to understand, predict, and counteract man-machine mismatches (Woods et al., in press). The following discussion of factors underlying mode errors of omission will start out by looking at the human element in the above outlined 'cognitive triad' (Woods and Roth, 1988). Pilots' approach to monitoring the automation on advanced technology aircraft will be examined. Subsequently, factors related to the design of modern cockpit systems will be discussed in light of their incompatibility with pilots' monitoring approach. The impact of contextual factors on the interaction between man and machine will be pointed out at various points in the discussion.

## 5.1 Attention Allocation on the Flight Deck of Advanced Automated Aircraft

Mode errors of omission are symptoms of a lack of mode awareness which, in turn, is the result of a breakdown in the allocation of attention across and within cockpit displays. To understand the reasons for and consequences of breakdowns in mode awareness, this research started to examine pilots' monitoring strategies on advanced flight decks. In the survey, pilots reported that they no longer use a basic instrument scan to keep track of what the airplane is doing. In other words, they no longer follow a highly practiced pattern of recurrently sampling the same basic flight parameters. Instead, the primary objective of monitoring on advanced flight decks is the verification of expected automation states and behaviors. These automation-related expectations are formed based on the pilot's knowledge about input to the automation and based on his mental model of the system.

We can think of a mental model as a "series of paired-associates by which the user predicts, through a causal chain, outputs of a process given its inputs" (Carroll and Olson, 1988). It is formed by the user based on experience with and observations of system behavior (Wilson and Rutherford, 1989). The benefit of having such a system model is that it supports the user in "predicting future events, finding causes for observed events, and determining appropriate actions to cause changes" (Rasmussen, 1979). One reason why such a model is particularly important for operators of many current automated systems is the fact that these systems sometimes use a different approach to carrying out a task than does the operator (Lehner, 1987). For example, as explained by pilots in the survey, some automated systems are programmed to trade altitude for speed to some extent to minimize thrust variations during a descent. Pilots set different priorities -- they vary thrust to maintain both target altitude and airspeed as accurately as possible. Knowledge of such different strategies is important as it helps pilots avoid intervening with "normal" system behavior that seems unconventional from their point of view (see Wiener and Curry, 1980).

A mental model of the automation helps pilots form expectations of system status and behavior which guide their allocation of attention within and across cockpit displays. In other words, such a model supports pilots in knowing where to look next for relevant information. This expectation-or knowledge-driven active search for information dominates under normal operating conditions. In situations that do not allow for the formation of expectations, as in the case of system failures, pilots' attention needs to be captured by salient indications of the existing problem. These circumstances require a feedback design that is capable of supporting data-driven attention allocation (Moray, 1986). The abrupt onset of a visual stimulus, for example, is a powerful means of capturing attention (Yantis and Jonides, 1984) while static differences in stimulus qualities such as luminance or color do not trigger shifts in attention (Jonides and Yantis, 1988).

In that sense, both the pilot's knowledge and understanding of the system and the design of its interface contribute to the observability of a system under different circumstances. Consequently, breakdowns in mode awareness can occur for different reasons, all of which involve a mismatch between pilots' expectations and the actual condition and configuration of the automation. In some situations, pilot input results not only in the expected but also in some additional effect that was not explicitly commanded and may therefore be overlooked. In other cases, the system may initiate an action based on input from some source other than the pilot. As a consequence, the pilot does not expect any transition in automation behavior and may fail to look at corresponding indications at the right time. Or he may look at the indications but fail to understand their significance. The latter problem is related to the cognitively austere nature and the fragmentation of feedback on automation status and behavior. For example, flight mode annunciations appear at the top of the Primary Flight Display and show the current nominal status of the system. The associated targets for the active mode configuration are shown in various other locations on the PFD and on the FCU. Finally, the implications of the mode configuration in terms of automation behavior, i.e., in terms of input to flight controls and in terms of thrust management, are not reflected by corresponding behavior or movement of the controls but are rather shown by means of symbolic representations on the ECAM displays. This fragmentation of information on the status and behavior of the automation across different displays requires mental efforts on the part of the pilot in order to put together a picture of the overall system configuration and to understand its implications.

## 5.2 Properties of Advanced Automation and Their Contribution To Mode Errors of Omission

Many advanced automated systems have the potential to operate at a high level of authority and autonomy. They can act independent of (immediately preceding) pilot input and without requiring pilot consent. These system capabilities require a very effective communication between human and machine concerning goals and activities in the interest of coordination. To support this increased need for efficient information exchange, the development of improved system feedback would be necessary. This requirement follows from earlier research results which indicate that feedback even on less advanced flight decks is not adequate for supporting the relatively low demand for human-machine coordination with those systems (e.g., Wiener, 1989; Sarter and Woods, 1994). However, today's highly advanced flight decks still involve very similar indications of automation status and behavior. The development of feedback design has not kept pace with the increased demands created by changes in automation properties. The net effect of these opposing forces -- an increased need for feedback in combination with a stagnant availability of feedback -- is breakdowns in the mutual understanding and cooperation between human and machine.

In the following paragraphs, design factors and capabilities that contribute to the need for more effective communication and coordination will be examined in some detail. Their contribution to observed problems with mode awareness in our research as well as in recent incidents and accidents involving 'glass cockpit' aircraft will be discussed. Incidents and accidents will be presented for illustration purposes and, even more importantly, to provide evidence for the fact that mode errors of omission that were observed in the simulation study do in fact occur in line operations and are a major concern for the operational community.

### 5.2.1 Authority and Autonomy

Advanced automated systems are 'strong' in the sense of acting at a fairly high level of authority and autonomy. They can initiate an action without requiring (immediately preceding) pilot input -- autonomy -- and without having to verify the pilot's consent with their action -- authority. Input from a variety of sources other than the pilot (e.g., the co-pilot, sensors of the airplane environment, designer instructions) is capable of triggering automation behavior.

In many cases, the nature of the resulting behavior is determined by the system designer rather than the operator of the system. For example, in the case of envelope protection functions, the automation acts based on sensor input indicating that a predetermined threshold for a parameter such as bank or pitch angle is being reached. In response, the automation alters or overrides the pilot's input to recover according to designer instructions. In other words, the automation no longer remains subordinate to the pilot, thus violating one of the proposed requirements for human-centered automation design (Billings, 1991).

The high level of authority and autonomy that is exemplified by envelope protection functions has played a role in a recent incident involving an advanced 'glass cockpit' aircraft. During their final approach, the pilots on this flight had disconnected the automatic pilot while leaving the flight directors and the autothrust system engaged. In this configuration, the automation provides automatic speed protection, i.e., the automation prevents the aircraft from exceeding an upper and lower airspeed limit. At some point during the approach, after flaps 20 had been selected, the aircraft exceeded the upper airspeed limit for that configuration by 2 kts. The overspeed protection became active, and an automatic mode transition occurred from "vertical speed" to "level change". As a consequence of this mode change, the autothrottles moved to the climb power setting, and the aircraft pitched up sharply. The pilots were not aware of the mode change, and the pilot-in-command overrode the autothrottle back to the idle power setting without disconnecting it. Ultimately, the airplane pitched up to about 50 degrees, entered a sharp left bank and went into a dive. The pilots eventually disengaged the autothrust system and its associated protection function and regained control of the aircraft (Sparaco, 1994).

This incident is an example of a breakdown in the communication between man and machine about their intentions and understanding of the situation. The independence and power of the automation contributed to the described incident. But these system properties are not problematic per se. They merely create an increased need for information exchange in the interest of effective coordination of the activities of both agents. The observed problems are created by the fact that this new requirement is not supported by the development of improved feedback on the activities and reasoning of the system which would support the detection and understanding of mismatches between expected and actual system behavior. Most automated systems rather tend to be 'silent' in the sense of lacking communicative abilities. They do not know when to communicate with the pilot, what information is relevant, and how to present information to the pilot. Therefore, they do not support pilots in deciding when to look, where to look, and what to look for.

The combination of high authority and autonomy in combination with inadequate feedback is one contributor to the occurrence of errors of omission. There are other design features that contribute to the perception of the automation as an independent agent and that can prevent pilots from forming adequate expectations of system status and behavior. They will be explored in the following paragraphs which talk about coupling and complexity, about inconsistent automation behavior, and about the lack of situation awareness on the part of the machine.

### 5.2.2 Coupling and Complexity

Advanced automated systems involve a high degree of coupling and complexity. Complexity refers to the interaction between and the transitions across a large number of different automation modes (see figure 3 for an example of the proliferation of modes on an advanced flight deck). Coupling is a related property that refers to a system design where a particular input results not only in the expected and desired behavior but also has additional 'indirect' side effects (Woods, 1988). An example of such 'effects at a distance' from the simulation study is the runway change which, when entered by the pilot, automatically leads to the deletion of previously entered altitude constraints. This effect is neither commanded nor desired by the pilot, and it may lead to a violation if it is not detected in time to recover.

The highly coupled and complex nature of advanced automated systems has played a role in a recent accident involving confusion on the pilots' part about the active vertical mode on an advanced 'glass cockpit' aircraft (Sparaco, 1994). One scenario that has been proposed to explain the accident is that the crew originally set up the automation to fly in the TRACK/FLIGHT PATH ANGLE mode, a combined mode related to both lateral (TRACK) and vertical (FLIGHT PATH ANGLE) navigation. When they were given radar vectors by the ATC controller, they may have switched from the TRACK to the HDG SEL mode to be able to enter the heading requested by the controller. However, pushing the button to change the lateral mode also automatically changes the vertical mode from FLIGHT PATH ANGLE to VERTICAL SPEED -- the mode switch button affects both lateral and vertical navigation. When the pilots subsequently entered "33" to select the desired flight path angle of - 3.3 degrees, the automation interpreted their input as a desired vertical speed of 3,300 ft. This was not intended by the pilots who were not aware of the active 'interface mode' and failed to detect the problem. As a consequence of the too steep descent, the airplane crashed into a mountain.

It is important to point out that "the existence of many parts is no great trouble for either system designers or system operators if their interactions are expected and obvious." (Perrow, 1984). In other words, as long as system behavior is consistent and clearly indicated, and as long as the operator has an appropriate model of the system that leads to proper expectations and allocation of attention, complexity and coupling may not be a problem. But some of these prerequisites are not fulfilled on current automated flight decks. For example, advanced automated systems do not always behave in a consistent way -- a problem that is discussed in the following section.

### 5.2.3 Inconsistent Design of Automation Behavior

The mental model of the automation is the basis for pilots' expectations of system status and behavior. Breakdowns in mode awareness have been attributed to gaps or misconceptions in operators' mental model in the context of earlier research on human-automation interaction (Sarter and Woods, 1994; Cook et al., 19...; Norman, 1983). However, mismatches between expected and actual automation behavior are not necessarily related to an inadequate model. They can also result from inconsistent automation behavior.

The term 'consistent' is used in this context to refer to a design where "a similar task or goal should be associated with similar or identical actions" (Carroll and Olson, 1988). Consistency is a system property that affords the human operator predictability of system states and actions (Billings, 1991) based on inferred rules about input-outcome associations. If a system suddenly (re)acts to the same input in a different way, it is impossible for the pilot to anticipate this behavior which, in turn, makes it less likely to be observed.

An example from the simulator study is the scenario event of the go-around below 100 ft AGL. Pilots had learned from prior experience with the system that applying TOGA power leads to the activation of the autothrust system. This statement is true in all situations except the go-around below 100 ft AGL where TOGA power leads to the disengagement of autothrust. Pilots are not likely to know about this exceptional behavior as it involves a rare event that pilots hardly ever encounter in line operations. Consequently, they expect the autothrust system to manage thrust for them, and they are surprised to observe aircraft behavior that suggests the opposite.

While this mismatch between expectation and actual behavior was relatively easy to detect, pilots still experienced difficulties with understanding and handling the situation. In part, this may be explained by the highly dynamic nature of the event. There was no time for thought experiments (Rasmussen, 1979) or the mental simulation of system behavior (Klein and Crandall, 1993) to explain the situation. In addition, the strength of the input-outcome association in pilots' model may have been very high because they had a very large amount of prior experience with situations where TOGA power resulted in activation of the autothrust system -- after all, every takeoff involves this sequence of events. It is conceivable that pilots were convinced of the adequacy of their system model and therefore had difficulties to accept and explain what was happening. One of the pilots in the study referred to this experience as 'a moment of denial' which caused him to delay any reaction to his observations.

Another example of inconsistent automation design is related to the envelope protection function on some automated aircraft. A recent incident as well as a recent accident have been reported where pilots were surprised to find out about an exceptional circumstance where the automation fails to protect the airplane from an excessive pitch angle. In both cases, the problem occurred in a situation where the airplane was about to capture a target altitude. When approaching this altitude, the automation transitions to the so-called "ALTITUDE ACQUISITION" mode. This particular mode is the only case where the automation no longer provides pitch protection. Instead, the automation tries to attain the target altitude as quickly as possible without considering any possible risk factors. This situation involves two challenges for the pilot. He has to anticipate or notice the 'uncommanded' mode transition to the ALTITUDE ACQUISITION mode, and he has to know about and remember that this mode represents an exception to the rule of pitch protection.

In the case of the accident, an Airbus A-330 crashed during a test flight where pilots were trying to test the speed reference system of the automation in case of an engine-out. Just when the automation approached the pilot-selected target altitude for level-off and went into the ALT ACQ mode, the pilots shut down one of the two engines for test purposes. The automation continued to pitch up to reach its target altitude which, in combination with the simulated engine loss, resulted in a rapid loss of airspeed. Given their close proximity to the ground, it was not possible for the crew to recover from the situation.

In the other example, a B-757-200 experienced a similar problem during climb-out. Due to its low weight, the airplane climbed at a fairly steep rate. The high vertical speed led to a very early activation of the altitude capture mode at

2,200 ft with a target level-off altitude of 5,000 ft. As a consequence of entering this mode, the autothrottles reduced power for a smooth level-off, but the aircraft still pitched up to gain altitude. This combination of high pitch and low power again led to a rapid decrease in airspeed. In this case, the pilot was able to recover the airplane but he was surprised by the exceptional behavior of the automation.

These cases of unexpected system behavior are problematic because they do not represent adaptive responses to changing circumstances. In other words, the change in system behavior is not related to contextual factors that warrant or require a deviation from standard behavior. Instead, the inconsistent behavior occurs for reasons that are not transparent to the pilot and at busy times when the pilot needs to be able to rely on the automation. Particularly with respect to critical features such as protection functions, it can therefore be argued that system behavior should be consistent or homogenous throughout all control modes.

### 5.2.4 The Lack of Situation Awareness on the Part of Cockpit Automation

*"..there is a profound and persisting asymmetry in interaction between people and machines, due to a disparity in their relative access to the moment-by-moment contingencies that constitute the conditions of situated interaction." (Suchman, 1987)*

So far, we have discussed possible reasons for the lack of situation or, more specifically, mode awareness, on the part of the pilot. But current automated cockpit systems are not fully embedded in context either -- they are sometimes 'out-of-the-loop'. They can access only a limited section of all relevant flight-related data on their own.

The fact that the automation has only limited sensor-mediated access to information about its situation seems to have played a role in a recent accident where it was impossible for the pilots to provide a critical piece of information to the system. This crash is related to the logic of the automation with respect to the availability of braking devices upon landing. The automation only allows for thrust reverser deployment if sensors indicate strut compression on both main landing gears. With full flaps extended, spoilers can only be deployed if the tires on both main gears indicate a speed of more than 72 kts or when strut compression is sensed in combination with a radio altimeter reading of less than 10 ft. For the automation, these sensor inputs are the only source of information to determine whether or not the airplane has landed.

In this accident, neither one of the two braking devices could be utilized by the crew to stop the airplane on the available runway. What happened? The crew was informed by ATC of crosswind conditions and consequently landed the airplane "into the wind", i.e., the airplane first touched down with only one of the two main landing gears. The sensor input indicating that only one instead of both landing gears had ground contact did not match the automation definition of a landing and therefore made it impossible for the crew to deploy thrust reversers or spoilers for nine seconds after touchdown. The airplane could not be stopped in time to avoid an overrun of the runway.

While the pilots in the above example did not have a chance to inform the automation of the fact that the airplane had in fact landed, the crew is more often required to play the role of an intermediary between the world and the system.

This requirement creates a number of problems. The pilot has to keep track of what the automation already knows and what it needs to be told. The required information has to be translated into the machine's language, and it has to be entered by means of a cumbersome interface. These requirements are particularly problematic in situations where the amount of information is very high and where pilots are already busy with other tasks as in the case of an approach. In other words, they represent an example of the "clumsy" use of automation (Wiener, 1989) where the system supports the pilots least or even gets in his way when he needs help most.

In contrast, successful and efficient human-human interaction is possible because "in working with people, we establish domains of conversation in which our common pre-understanding lets us communicate with a minimum of words and conscious effort" (Winograd and Flores, 1988; see also Johannesen, 1994). If man and machine are to cooperate effectively, the automation therefore needs to be designed to minimize the mental efforts required from the pilot in the interest of maintaining mutual understanding and coordination. Otherwise, "breaches in understanding that for face-to-face interaction would be trivial in terms of detection and repair become 'fatal' for human-machine communication" (Suchman, 1987).

The detection of misunderstandings between man and machine can be very difficult due to sometimes subtle indications of a discrepancy between expected and actual behavior. Still, this task is very important in the context of highly autonomous systems in the interest of a timely recovery from errors. In that sense, the primary task of operators of advanced automated systems is sometimes misrepresented as the detection of system failures. Failure detection is supported by many of today's systems that are capable of self-diagnosis. The much more difficult task for pilots on advanced flight decks is the detection of system behavior that is normal but not appropriate given the current situation and intentions of the pilot. This problem is aggravated by the possibility of a partial overlap between such inadequate system behavior and the behavior desired or intended by the pilot. Given that the pilot and the system do not communicate at the level of intentions, it is impossible for the automation to realize that its behavior does not match the pilot's goals. Norman (1990) has therefore suggested that "current automatic systems have an intermediate level of intelligence that tends to maximize difficulties". In his view, we need "higher levels of automation, some forms of intelligence in the controls, an appreciation for the proper form of human communication that keeps people well informed, on top of the issues, but not annoyed and irritated."

Note that Norman is not talking about 'higher levels of automation' in the sense of a system that is capable of performing more flight-related functions for the pilot. Instead, his remarks emphasize the need for a system that is capable of being a 'team player' in the sense of recognizing the need to coordinate activities with the human operator by keeping him informed about the own status, behavior, intentions, and limitations (Woods et al., 1991).

One prerequisite for achieving the goal of such collaborative automation is a transparent and consistent system design that supports operators in monitoring, anticipating, and learning from system behavior. Progress with respect to this objective requires a better understanding of stimulus properties that are capable of guiding or attracting attention (Cowan, 1988). In order for the automation to effectively communicate with the operator, it also needs to be provided with means to determine whether its behavior has been observed, understood, and agreed to by the operator. The automation can not continuously second-guess the pilot without becoming a nuisance. This is particularly true in the case of highly dynamic high-tempo situations which involve intense pressure and a minimum of information-processing capacity on the part of the operator (Doerner, 1983).

A complementary approach to improving the coordination between man and machine is through modifications of training approaches. Currently, training is often assigned the role of a fix for bad design. It is expected to help pilots cope with shortcomings in system design that should instead be eliminated. The main objective of training for automation should rather be to support the formation of a mental model through active system exploration. Explicitly teaching the model of a system has been shown to run the risk of creating "inert" knowledge that can not be activated and applied by the practitioner when necessary (e.g., Feltovich et al., 1991 ). Training also needs to help pilots develop effective monitoring strategies for advanced automated flight decks, an area that seems to be neglected in current training according to pilots in our survey.

Finally, as it is very unlikely that errors can be completely eliminated, a better understanding of error detection and recovery is needed. For example, a large number of incident reports involving mode error in the aviation domain suggest that error detection is most often based on observations of undesired airplane behavior rather than on the discovery of unexpected automation states. It is not clear what serves as an effective cue in these cases to redirect the operator's attention from verifying system states to checking aircraft behavior.

Why are the same cues not observed in different circumstances leading up to accidents?

### 5.2.5 Concluding Remarks

The results of this research provide insight into the impact of technological change on the interaction between man and machine. Clearly, the problems that were identified in the course of this study can only be addressed successfully by considering the impact of any intervention on all three components of the 'cognitive triad' - human, machine, and environment - and on their mutual interaction. In that sense, the most desirable philosophy of automation may be team- rather than human-centered in the sense of creating a cooperative man-machine ensemble where both the human and the machine support one another in their different tasks.

# *APPENDICES*

## Appendix A - Survey Questionnaire

*Dear [airline name appeared here] Pilot:*

This questionnaire is part of a joint research project between [airline name appeared here] and The Ohio State University on pilots' experiences with the automation on the Airbus A-320. The project is being sponsored by NASA-Ames Research Center in the context of the National Aviation Safety/Automation Plan. The focus of this joint effort is to identify problems that may arise in the interaction between you and the automated systems in your cockpit. Understanding these problems will enable us to better support and train pilots in the future. To achieve this goal, we need more feedback from you concerning your experiences with the Flight Management System (FMS) on the Airbus A-320.

We have developed the attached questionnaire as a first step in our joint research efforts. In this questionnaire, we would like to ask you to provide information concerning your experiences with training for and line operations of the A-320 FMS. Some of our questions are fairly specific while others leave room for comments on issues that you may find important to mention. This questionnaire is important for us to understand your strategies of automation usage, to identify any difficulties that you may experience with the operation of the system, and to get your input concerning possible improvements of FMS training and design. Therefore, please view this questionnaire as an opportunity for you to have an impact on the focus and further activities within this project.

To be able to interpret your input, we also ask a few questions concerning your flying background. Please note, however, that this is an anonymous survey. In order to guarantee the confidentiality of your answers, please do not write your name or any other possible identification on any of these pages. After completing this questionnaire, just use the enclosed prepaid envelope to send it back to our lab at the Ohio State University.

***Thank you very much for your cooperation in sharing your experiences with us!***

If you would like to get in touch with us, please feel free to give us a call at the Ohio State University. Our phone number is (614) 292-6287 (Nadine Sarter).

*Background Information*

1) Your Age: ........ years

2) How much total flying time do you have (excluding flight engineer time) ?

.................... hrs

3) Please fill in the following table concerning your flight experience:

Table 8. Flight Experience of Pilots Responding To The Survey

| | Aircraft | Glass Cockpit | Seat | Hours | Airline |
|---|---|---|---|---|---|
| Current | A 320 | yes | | | |
| Previous | | | | | |
| Previous | | | | | |
| Previous | | | | | |
| Previous | | | | | |

*Operation and Design of the A-320 FMS:*

Previous studies have shown that pilots are sometimes "surprised" by what the automation is doing or fails to do for them. We would like to know from you whether you have had such experiences as well. In case you have, please describe in some detail up to three situations in which the automation behaved in an unexpected way.

1a) Have you ever been "surprised" by the automation on the A-320 ?

O yes O no (in this case, please go to question 2)

1b) Please describe in some detail up to three situations in which you were surprised by the automation (please use the reverse side to continue with your descriptions). We are interested in how you reacted to and coped with this "surprise", and how you managed to explain it (e.g., did you find an explanation on your own, with the help of the other pilot, by looking at a manual, by asking an instructor?).

6a) On "glass cockpit" aircraft such as the Airbus A-320, a large amount of information on flight-related parameters has been integrated on the PFD. Please describe to us how this has affected your "scan", e.g., how do you pick up information from the PFD ? Did you develop a new kind of scan ? If so, please try to describe your scanning pattern and behavior. How long did it take to develop a scan ?

**Once again, thank you very much for sharing your experiences with us !**

## Appendix B - Pilot Reports of 'Automation Surprises' (n<5)

| | |
|---|---|
| Failure to intercept LOC due to high speed/intercept angle | 3 cases |
| Unsuccessful attempts to V/S through FCU altitude | 2 cases |
| Missed approach after forgetting to arm APPR | 2 cases |
| CLB THRUST as consequence of arming APPR | 2 cases |
| Disengagement of APPR mode when activating secondary flight plan for new runway | 2 cases |
| VNAV calculations unclear | 2 cases |
| Turning due to switching from HDG SEL to managed NAV without cleaning up flight plan | 1 case |
| Impossible to tune ILSs separately for approach | 1 case |
| Bank angle limits change depending on speed | 1 case |
| Input ignored when not pushing FCU buttons hard enough | 1 case |
| Open Descent mode flies aircraft through selected altitude if speed brakes not retracted early | 1 case |
| Activating managed NAV after arming APPR results in LOC capture only | 1 case |
| Speed increase with turning on FD during visual approach | 1 case |
| ATHR does not arm on TO as consequence of activating secondary flight plan | 1 case |
| FMGC drops destination when being vectored over it | 1 case |
| Loss of constraints in EXPEDITE mode | 1 case |
| 1 FD on is controlling for ATHR | 1 case |
| Logic of Ground Speed Mini unclear | 1 case |
| Loss of VNAV when leaving managed lateral NAV | 1 case |
| Slight pitch up when extending flaps 1 for landing | 1 case |

## Appendix C - Acronyms

| | |
|---|---|
| A/C | Aircraft |
| ACARS | Automatic Communication and Recording System |
| ADF | Automatic Direction Finder |
| AGL | Above Ground Level |
| AOM | Aircraft Operating Manual |
| AP | Autopilot |
| APPR | APPROACH mode |
| ATC | Air Traffic Control |
| ATHR | Autothrust System |
| Cat II | A CatII approach involves weather minimums of a 200 ft ceiling and 2,600 ft RVR |
| CLB | Climb Detent of the Thrust Levers |
| COM | Cockpit Operating Manual |
| ECAM | Electronic Centralized Aircraft Monitor |
| EFIS | Electronic Flight Instrument System |
| FADEC | Full Authority Digital Engine Control |
| FAR | Federal Aviation Regulations |
| FCU | Flight Control Unit |
| FD | Flight Director |
| FMA | Flight Mode Annunciations |
| FMGC | Flight Management and Guidance Computer |
| FMGS | Flight Management and Guidance System |
| FPA | Flight Path Angle mode |
| G/S | Glideslope |
| HDG SEL | Heading Select Mode |
| hrs | Hours |
| IAS | Indicated Airspeed |
| ID | Identifier |
| ILS | Instrument Landing System |
| kts | knots |
| LAX | Identifier for Los Angeles |
| LOC | Localizer |
| MCDU | Multi-Function Control and Display Unit |
| MCT | Maximum Continuous Thrust |
| MDA | Minimum Descent Altitude |
| ND | Navigation Display |
| NDB | Non-Directional Beacon |
| PF | Pilot-Flying |

| | |
|---|---|
| PFD | Primary Flight Display |
| PNF | Pilot-Not-Flying |
| PPOS | Present Position |
| PROG | Progress Page on MCDU |
| RMPs | Radio Management Panels |
| SOPA | Standard Operating Procedures |
| SPD | Speed Mode |
| TCAS | Traffic Collision and |
| TOGA | Takeoff-Go-Around |
| Vls | Lowest Selectable Airspeed |
| VNAV | Vertical Navigation |
| VOR | Very high frequency OmniRange Navigation System |
| V/S | Vertical Speed (mode) |
| VTU | Ventura VOR |

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