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Cognitive Mismatches in the Cockpit: Will They Ever Be a Thing of the Past?

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Abstract

Changes in aviation over the last thirty years have dramatically affected the way that flight crews fly aircraft. The implementation and evolution of the glass cockpit, however, has happened in an almost *ad hoc* fashion, meaning that it does not always properly support the flight crew in carrying out their tasks. In such situations, the crew's mental model of what is happening does not always match the real state of affairs. In other words there is a cognitive mismatch. An initial taxonomy of cognitive mismatches is defined, and the problem illustrated using an example from an aviation accident. Consideration is then given to how cognitive mismatches can be managed. A call is made for the development of an integrated cockpit architecture that takes better account of human capabilities and allows for new developments to be added to the cockpit in a more seamless manner.

Keywords
Cognitive mismatches, flight deck systems, human-machine interaction.

INTRODUCTION

Mastering a complex skill, such as flying an aircraft, typically takes of the order of 1000 hours (Schneider, 1985). When learning to fly an aircraft, pilots were traditionally taught to aviate, navigate and communicate. The way in which they carry out these high level tasks has changed in line with the significant changes in the flight deck environment over the past 30 years.

Up until the early 1970s, the flight deck was dominated by mechanical and electro-mechanical devices, such as airspeed and altitude indicators. Later versions of these traditional technologies included early implementations of several of the instruments used today, such as the ground proximity warning system (GPWS). It was the introduction of cathode ray tube (CRT) displays, though, that heralded the dawn of the era of the glass cockpit, with the pioneers being Boeing (B747-400), McDonnell Douglas (DC-10) and Lockheed (1011) (see Billings, 1997 for a detailed account of the evolution of aviation automation). The transition to the modern glass cockpit was a gradual one. Initially, only some of the electro-mechanical instruments were replaced by what were essentially digital equivalents of the older analogue versions, such as the flight director. Part of the reason for this was that it made it easier for pilots to switch between aircraft with the older and newer displays, without having to obtain a new type rating from the aviation authorities. The traditional "one value-one display" rule was broken when multi-functional displays were introduced, one example being the integration of the traffic collision avoidance system (TCAS) with the graphical navigation display, which also allowed some de-cluttering of the cockpit by reducing the number of individual display instruments.

Whilst the face of the new cockpit was its CRT displays, its heart was provided by microprocessor technology. The most obvious intrusion of computers aboard aircraft was the flight management system (FMS) which provides flight functions such as the storage and execution of pre-programmed flight plans. The new technology also provided crews with ways of automatically optimising low-level functions, such as fuel management, during a flight.

Another radical change occurred in 1988 when Airbus introduced fly-by-wire aircraft, with the A320, in which the control surfaces (flaps, slats, rudder, elevators and so on) are operated by electric actuators rather than steel rods and cables. This coincided with the use of small side sticks to replace the much larger conventional control yoke, which made visibility of several of the displays easier. Since then, computers have played an ever-increasing role on the flight deck, helping to optimise the task of flying the plane, and sometimes relieving the pilots of tasks. Most recently there has been a move towards highly graphical user interfaces (e.g., Sanfourche, 2001), and in the new Airbus A380 palm-based technology will be used by pilots to carry flight plans onto the flight deck where they will be downloaded into the FMS.

Part of the motivation for the increased automation was the need for increased safety in light of the continuing rise in the levels of air traffic (Orlady & Orlady, 1999). Some of this burden for handling safety and efficiency has passed to the automation, such as the detection of other aircraft in the vicinity which is handled by the aforementioned TCAS. The net effect of the technology on safety is not clear-cut, although the accident numbers show a stable downwards trend since 1992 despite increasing numbers of passengers (Ranter, 2005).

The introduction of the glass cockpit heralded the move to reduce the size of flight crews from three to two, with the Flight Engineer being removed. Several of the tasks previously performed by the Flight Engineer, including the management of equipment failures, were handed over to the automation. It was hoped that the glass cockpit would also reduce the amount of pilot training required, but this has not been the case (Orlady et al., 1999). Whilst many pilots agree that modern aircraft are easier to fly, closer inspection suggests that their workload has shifted, rather than reduced, so pilots now have to carry out more supervisory tasks. The pilots' lack of visibility of concurrent modes and automated tasks leads to difficulties in predicting the outcome of actions. Indeed, pilots have reported increased problems in understanding and anticipating aircraft behaviour, and in tasks such as programming the FMS (Rudisill, 1995). This means that there is an increased likelihood of pilots spending more time with their heads down, interacting with the automation, rather than focusing their efforts on the primary task of flying the aircraft. In order to deal with this situation, pilots have to expend more time and effort learning how to manage these new systems, although training is normally tailored to mitigate against this. These changes mean that pilots are now taught to aviate, navigate, communicate *and* manage systems.

There are already several well-documented examples of the problems introduced by the technology. Automation surprises (Sarter et al., 1997), for example, arise when the technology autonomously performs tasks that cause the aircraft to behave in a manner that the pilots had not anticipated. The ways in which the pilots use the technology is a recognised problem and, as a result, much of human-machine interaction (HMI) research is now concerned with the reliability of the dialogue between humans and modern flight deck systems (FAA Human Factors Team, 1996). Whilst it is accepted that cognitive processes are fallible, a solution in terms of a reliable interaction has not been forthcoming, and automation surprises remain an ongoing concern.

Cognitive mismatches occur when there is a disparity between the operator's mental model of the system, and the way that the system is really working (e.g., Rushby, 1999). This paper considers the general problem of cognitive mismatches and how they can be managed. Given the importance of the dialogue between the human pilot and automated systems in the modern aviation environment, the wider aim is to examine the role of human-machine cooperation in the failure of safety-critical systems. The relationship between mental models and cognitive mismatches is considered in the next section. Section 3 then illustrates the problem using an accident where a non-assistive cockpit prevented the recovery of a piloting error. Consideration is then given to the available options for dealing with cognitive mismatches in the cockpit in Section 4.

MENTAL MODELS AND COGNITIVE MISMATCHES

The way that crews fly an aircraft is generally considered as a typical control loop activity. The pilots have some sort of internal representation—a mental model—of how the socio-technical system (pilots, aircraft including computer-based systems, air traffic control, the airline company, and the regulators) operates. This mental model is usually developed as a result of training and experience in doing the job, and is used to reason about the socio-technical system and control the underlying processes (e.g., Moray, 1996). Mental models are used by the pilots to determine which system variables to monitor, and the pilots interpret the values of these variables to update their mental model of the current state of the system. They then compare this model of the current state with the expected state, and make adjustments to the system as necessary to try and ensure that the current and expected states match. This process can be summarised by the simplified loop shown in Figure 1.

Figure 1 about here

In many modern complex control systems, including aircraft, there are usually too many variables for the operators to check them all individually whilst still controlling the system or process in a timely manner. Pilots deal with this problem by learning which variables can normally be used to reliably predict the system's current state, and then monitor that subset of variables. In other words, the pilots rely on their perceived state of the system, rather than the real state (Boy, 1987). Generally, this works well, but when conditions deviate from the normal the pilots may misinterpret the system state which can give rise to further problems if they base their actions on an incorrect interpretation of the real state of the system (Baxter & Ritter, 1999).

As the complexity of aircraft cockpits continues to increase, the chances of the pilot’s mental model being accurate are accordingly reduced. Instead of being an isomorphic representation of the real world—in which each point in the mental model corresponds to a point in the real world—the pilot’s mental model is a homomorphic representation—each point in the mental model corresponds to several points in the real world (Moray, 1988). In other words, the model only accounts for the states that the pilots have previously encountered (an isomorphic model would require the pilots to either have to know, or else be able to generate all the system’s possible states). The pilot’s mental model is therefore a simplified representation of the real situation and as novel situations and states are encountered, the model’s limitations start to become apparent.

In aviation, a cognitive mismatch occurs when the pilot’s mental model of the system does not adequately describe the way that the system is working. The consequence is that the operator may not be able to explain or predict the aircraft's behaviour. There are many possible causes but they are often rooted in the design of the automation and how the pilots have to use it. Failures in HMI often arise because the interface fails to provide appropriate support for the crew to carry out their required tasks (Sherry et al., 2002). This lack of transparency in the automation’s user interface makes it harder to manage the system because the pilots cannot readily comprehend what the system is doing.

Cognitive mismatches can take many forms, such as mode confusion (Palmer, 1995) where the pilots believe that the automation is operating in one mode, whereas it is actually operating in a different mode. Mode confusion plays a part in automation surprises, particularly when performing the same action leads to different effects in the different modes. The various types of cognitive mismatch can be categorised using two dimensions (see Table 1):

- *Type of mismatch*. A *real* mismatch occurs when there is an actual discrepancy between the pilot's mental model and the way that the system operates. This state of affairs is normally indicative of a flaw in the pilot's mental model. A *perceived* mismatch occurs when the pilot perceives that there is an actual discrepancy between their mental model and the way that the system operates, when in reality there is not. In other words, this state of affairs represents a false alarm.

- *Detection of mismatch*. The detection of a mismatch provides a potential trigger for action, so that the mismatch can be corrected. Normally this would require some diagnostic activity. If a mismatch is undetected, this means that the pilots are unaware that the situation is potentially deteriorating.

Table 1 about here

There is an implicit temporal dimension to cognitive mismatches. The pilots need to be able to detect the mismatch when they can still diagnose the problem and take recovery action before any adverse consequences arise. Ideally, all real mismatches should be detected, or at least made apparent to the pilot so that they can be managed in a timely manner. Detection is not always straightforward, however, because cognitive biases can intervene, such as falsely attributing explanatory power to unrelated events which happen coincidentally. In the Kegworth air accident in the UK in 1989, for example, the pilots shut down the right engine, which they believed to be faulty, and this coincided with a reduction in vibration and smoke and fumes from the faulty left engine. The pilots assumed that they had fixed the problem and sought to make an emergency landing (Besnard et al., 2004). The problem of cognitive mismatches are illustrated in the next section using data from an aircraft accident report.

TAIL-FIRST LANDING AT NAGOYA

On April 26th 1994, an Airbus A300-600 (a glass cockpit, but not fly-by-wire aircraft) left Taipei (Taiwan). Two hours and 22 minutes later, the aircraft crash-landed tail-first at Nagoya (Japan), killing 264 of the 271 people onboard (Ministry of Transport, 1996). A complex interaction between the Go-around mode, autonomous inputs from the trimmable horizontal stabilizer (THS), and thrust variations contributed to the crash.

During the final stage of the approach, 100 seconds from impact and at an altitude of 1070 ft, the Go-around mode had been erroneously engaged by the First Officer (FO) who was flying the aircraft. In this mode, the aircraft applies maximum thrust and climb rate to regain altitude. Five seconds after engaging Go-around mode, the Captain noticed the FO's mistake and called out for the mode to be disengaged; this was not done. The Go-around mode caused the aircraft to climb above the intended glide path. The FO tried to bring the aircraft's nose down and decrease the thrust. The aircraft resisted the nose-down command, although it did level off temporarily at 1040 ft, and the FO managed to throttle back the engines. At 87 seconds before impact, the autopilot was engaged. This caused the THS to take control of the aircraft's attitude. At 68 seconds from impact, the aircraft started to pitch up again; four seconds later, the first officer disengaged the autopilot. At 48 seconds from impact, the angle between the wing and the airflow—the angle of attack—was still increasing, giving the aircraft greater lift. Given the low airspeed, the Alpha-floor protection triggered an automatic recovery from the near-stall conditions and the aircraft resumed climbing at 570 ft. The Captain took over the controls but could not lower the aircraft's nose to halt the climb. At 34 and 24 seconds from impact, the Captain verbally expressed his puzzlement and worries about the aircraft's behaviour. The increasing nose-up attitude could not be controlled and the thrust being set back and forth several times only worsened the situation. At 19 seconds before impact, the A300 went into a stall at a 52º nose-up attitude. The crew attempted several unsuccessful corrective actions on the ailerons and rudder, but the aircraft crashed tail-first at Nagoya.

The most obvious indication that this was a cognitive mismatch comes from the FO's attempts to counter the effects of being in Go-around mode—maximum thrust and climb rate—rather than just disengaging it (which the Captain had suggested). This was then followed some time later by the captain's verbal expressions of puzzlement about the aircraft's behaviour. The situation was exacerbated by the flight deck technology because the aircraft had automatic yoke-force disengagement inhibited below 1500 ft. Had it been enabled, the autopilot would have disengaged when the crew applied pressure on the yoke to bring the aircraft's nose down.

This example highlights some of the problems that can arise when a cognitive mismatch occurs and shows that the consequences of an unrecovered cognitive mismatch can be fatal. In this case the sheer amount of competing automation made it difficult to detect and resolve the cognitive mismatch. It is therefore important that flight crews should be made aware of the potential for cognitive mismatches to occur so that they can guard against them. Ideally cognitive mismatches should be prevented, or at least mitigated where possible. The next section considers how mitigation of cognitive mismatches can be achieved.

COPING WITH COGNITIVE MISMATCHES IN THE COCKPIT

The issue of cognitive mismatches needs to be considered carefully during the design of aircraft systems. More and more new automation has been introduced into the cockpit in an almost *ad hoc* fashion, without full consideration of the overall impact on all the other parts of the aviation socio-technical system.

Many of the new devices that have been added to the cockpit, such as the enhanced ground proximity warning system (EGPWS) and TCAS, contribute to safety. They detect when an unsafe situation has occurred and indicate this to the pilots, generating warnings and alarms, and potentially triggering automatic behaviours. For instance, some flight configurations (e.g. a low aircraft altitude with the landing gear still retracted) will automatically trigger several simultaneous alarms. If the low altitude flight was unintended, then the proliferation of alarms can hinder recovery—a lesson learnt from the Three Mile Island nuclear accident (Kemeny, 1981). If the low altitude flight was deliberately intended, however, then the multiple alarms will be an unnecessary distraction for the pilot.

Generally, the way in which safety is handled by the automation varies somewhat across different aircraft manufacturers. These differences reflect the manufacturer’s implicit assumptions about the pilot’s role: Boeing pilots have to decide what to do; Airbus pilots are advised what to do; and McDonnell Douglas pilots are told what has been done (Hicks & de Brito, 1998). This makes it hard for pilots to easily switch between the different manufacturers’ aircraft.

The management and programming of flight systems is now intrinsic to flying an aircraft. Pilots acknowledge that they allocate an increasing amount of their time to typing data into the flight management computer, thereby spending correspondingly less time monitoring external visual cues and focusing on the main task of flying the aircraft (Billings, 1997). Each new piece of automation adds to the systems management task and does not always provide a corresponding reduction in workload on the other tasks in the cockpit: the workload has shifted rather than reduced (Woods et al., 2002).

Given the current state of affairs in aircraft cockpits, the problem is how cognitive mismatches can be detected and managed in a timely manner or, preferably, prevented. Where prevention is not possible, the mismatches should be made obvious to the flight crew so that they can attempt to manage them. In other words, some effort should be made to ensure that the only type of mismatches that occur are those that are real (see Table 1) and that they are detected at the earliest possible opportunity. Some possible ways of dealing with the problems of cognitive mismatches are discussed below.

Do Nothing

The simplest solution is to maintain the status quo and continue to rely on pilots to detect, diagnose and fix any problems. This may be the only solution for some systems, particularly where there is limited scope for updating the cockpit technology, in which case pilots need to be continually made aware of any new potential problems with the new technology (through feedback from incident reporting systems, for example).

Keeping pilots in the loop has long been recognised as the best way to exploit human flexibility and adaptability (Bainbridge, 1987). As systems continue to get more complex, however, it may get even harder to keep the pilots fully in the loop, because they will require more complex mental models to appropriately represent the system's behaviour.

This is likely to make it even more difficult to detect any cognitive mismatches in a timely manner.

Under normal operating conditions, everything works fine. During busy periods, such as transitions between flight levels, however, if a problem is flagged up by the automation, this can lead to further difficulties. In particular, if crews have to diagnose automation problems, they will be correspondingly less involved in monitoring and controlling their other tasks. Re-introducing the third flight crew member (the Flight Engineer) into the cockpit may help. It could also adversely affect the current dynamics of the system, however, due to the need for extra communication, for example. The nature of the communication is also likely to be somewhat different because the automation now performs several of the functions that were previously the responsibility of the Flight Engineer, such as failure management.

Use Intelligent Assistants

The second solution is to utilise intelligent assistant technology, which is consonant with the joint cognitive systems approach (Hollnagel & Woods, 2005). Here, the idea is to develop and maintain a synergy between the operator's intentions and the computer system's model of the operator's behaviour. This is achieved by the intelligent assistant tracking the pilot's behaviour and comparing it to stored reference plans. The assistant then infers operational objectives, flags up identified errors, and generally provides support and assistance to the crew. These ideas have been implemented in systems such as Hazard Monitor (Bass et al., 1997), the Cockpit Assistant System, CASSY (Onken & Walsdorf, 2001), and the Crew Activity Tracking Systems, CATS (Callantine, 2001). Whilst all three systems have been tested using flight simulators, none are currently deployed in commercial aircraft.

The crash-landing at Nagoya described above provides an example of where intelligent assistants could help. CATS, for instance, compares the pilot's actions with reference plans. Before it flags an error, CATS waits until all the possible routes to the accomplishment of the inferred objective have been exhausted. Then, and only then, does it flag an error. In trials, CASSY detected all the pilot’s errors and 94% of its inferences about the pilot’s intentions were correct. CASSY also provides the capability to replan the flight and propose the available options following changes in instructions from ATC, or after a required Go-around manoeuvre, for example

Simply flagging an error would not have prevented the crash at Nagoya; the Captain had already detected the engaged Go-around mode. However, combining CATS' error detection capability with various degrees of authority delegated to the automation (as used in Hazard Monitor), could provide one way of efficiently compensating for human errors.

Patch the Existing Cockpit Design

There is often a long lead time in aviation between the initial design of a new technology and its introduction into the cockpit. Mode S datalink, for example, was originally designed in 1975, but has only required to be fitted to new aircraft flying under visual flight rules (VFR) since 2005 in Europe. A radical overhaul of the cockpit is therefore unlikely in the short term. In many respects, the way in which new technology has been introduced can be considered as patching the existing system, albeit usually in order to improve safety, as previously noted.

As an interim measure, consideration should also be given to the application of existing proposed solutions to several of the problems of HMI in cockpit that are already well documented (e.g., Billings, 1997; Sherry et al., 2002). Five common design errors have been identified:

1. The need for crews to reformulate the mission task in order to use the automation.
2. The need for crews to recall action sequences in order to access the required input devices or information in the cockpit displays hierarchy.
3. The need for crews to remember the correct formats for data entry.
4. The lack of clear labels and prompts to indicate where to insert data.
5. The need for crews to expend significant mental effort manipulating the feedback provided by the automation to infer the intentions of the automation and verify and monitor the long-term effects of commands.

If the designers properly understand how the flight crew have to execute the mission tasks, this will make it easier to provide automation that will support the flight crew in performing those tasks (thereby preventing Error 1), and hence make it easier to overcome the other errors listed above. Errors 2, 3, and 4 can be mitigated in two connected ways. First, by using visual cues that enable flight crews to recognise what needs to be done and how. Second, by making the interface coherent such that access to the required functions is implemented using the devices on the control panel that is used for the task at hand. The general aim is to minimise the amount of information that has to be recalled by the flight crew to access the appropriate device and then format and enter data. Data formatting and data entry problems can be overcome by selecting commands and values from lists which guarantee that the data will be in the correct format—rather than force the crew to recall the relevant data from memory before manually typing it in. Error 5 can be mitigated by providing feedback in a format that is appropriate to the mission tasks at hand which allows the crew to reliably understand and predict the aircraft's behaviour.

Design a New, Integrated Cockpit Architecture

In the longer term, however, a more radical solution may be required. Current cockpits are the result of the evolution of the glass cockpit in a bottom up manner. New pieces of automation are added which often bring their own sets of interfaces, displays and methods of interaction. The purpose and often the basics of the design of the new equipment are normally known well in advance. It would therefore seem sensible to develop a top down integrated cockpit architecture that would provide a more structured, coherent basis for the next generation of cockpits. The new architecture would provide better support to the pilots in the task of flying the aircraft.

It is already widely recognised and accepted that it is important for pilots to keep ahead of the plane. One useful facility of the new architecture would therefore be a feature that allowed the pilots to predict the future state of the aircraft. Ideally this would allow them to ask 'what-if?' type questions about future possible situations. The answers to such questions could help in anticipating some of the problems of cognitive mismatches, because crews would be able to detect potential problems with particular courses of action. In other words, rather than just focusing on flagging up when things have already gone bad, anticipate and predict potential problems as a way of stopping things from turning sour (Woods & Sarter, 2000).

Another useful feature would be the interpretation of pilots' intentions. This feature is already present in intelligent assistants, which attempt to infer the user's intentions on the basis of their actions. The sequence of actions is compared to a library of reference plans to infer what the user is trying to do. Such a facility would help to avoid problems like those in the A300 landing at Nagoya. It would also help in the management of cognitive mismatches because the automation would detect and flag up inconsistencies between pilots' actions and the operational task requirements.

Although the integrated cockpit architecture should help to make flying safer, by providing better and more timely support to pilots, there are potential knock-on effects. If the new cockpit radically differs from existing ones, for example, pilots might have to undergo extensive retraining to learn to use it . The retraining itself may not be an insurmountable problem in that pilots have previously demonstrated their flexibility by adapting to glass cockpit and fly-by-wire aircraft. There would be an effect on the airlines, however, who would have to develop and pay for the new training programmes for pilots. There is also the related issue of in-type certification of pilots. Currently airlines often maintain a high degree of similarity between the different type of aircraft that they have in their fleet. This means that if a pilot is certified to fly one type of aircraft owned by the company, he may also be certified to fly one or more of the other types of aircraft owned by the company. Pilots would have to be re-trained to fly aircraft with an integrated cockpit architecture, and the differences between it and other aircraft may mean that the pilots could not be certified to fly both.

Outside the cockpit, the introduction of an integrated cockpit architecture would also have an effect on the airframe manufacturers and the airlines. In particular, the new aircraft would potentially require new (and expensive) certification.

SUMMARY

The modern cockpit is heavily populated with automated equipment that the pilots have to program and manage. Often each piece of equipment has its own way of working, and its own idiosyncratic user interface. The proliferation of equipment makes it harder for the pilots to understand what the system is doing and to predict what will happen next, leading to cognitive mismatches which the pilot has to detect and resolve in a timely manner. There is, however, no silver bullet that can be used to solve the problem of dealing with cognitive mismatches in the cockpit. It seems clear that continuing to allow the glass cockpit to evolve further, by adding more automation that uses visual display based interfaces can only make things worse in the long run. The introduction of an integrated cockpit architecture is likely to be more disruptive and more expensive in the short term. Given the long lead time for developments in flight deck equipment, however, the preferred solution is still to set in train the idea of developing an integrated cockpit architecture. This new architecture would better support pilots in the task of flying the aircraft through facilities that allow them to keep ahead of the plane and anticipate possible problems, including cognitive mismatches.

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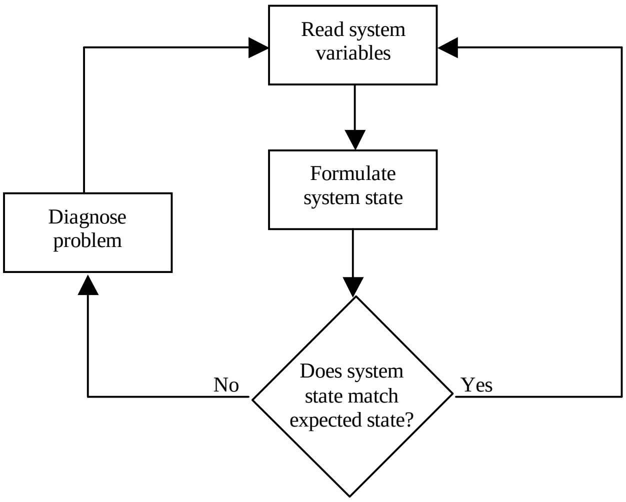

Figure 1. Simplified overview of pilot's control task

	Real mismatch	*Perceived mismatch*
Detected	Real problem: needs to be diagnosed and fixed.	False alarm: could be a problem if the pilots act and turn it an undetected real mismatch.
Undetected	Real problem that needs to be flagged to the pilots, so that it can be diagnosed and fixed.	Not possible: "perceived" implies "detected".

Table 1: The four theoretical types of cognitive mismatch.