HUMAN MEMORY AND COCKPIT OPERATIONS: AN ASRS STUDY

Dr. Jessica Lang Nowinski
NASA Ames Research Center
Moffett Field, CA

Dr. Jon B. Holbrook
National Research Council/NASA Ames Research Center
Moffett Field, CA

Dr. R. Key Dismukes
NASA Ames Research Center
Moffett Field, CA

Memory errors in the cockpit are often detected before they have negative consequences, but have also led to major aviation disasters. Our view is that vulnerability to such errors is not an indication of lack of expertise, but rather a function of the way normal human memory processes operate in situations involving routine, well learned behaviors. Approximately 6% of a random sample of 1299 Aviation Safety Reporting System (ASRS) reports analyzed were found to describe memory failures by pilots. These 75 reports were then categorized according to four themes: monitoring, absence of cues, habit capture, and poorly formed intentions. The cognitive mechanisms underlying these four types of memory errors are discussed as well as potential strategies for reducing vulnerability to errors.

Introduction

On August 16, 1987, Northwest Airlines flight 255 crashed just after takeoff, killing all on board. The NTSB concluded that the accident was caused by "the flightcrew's failure to use the taxi checklist to ensure that the flaps and slats were extended" (NTSB, 1989). This accident is a sobering example of the potential consequences of memory errors in flight operations. Unquestionably the crew intended to set the flaps, and had successfully remembered to do so on many other occasions. So how is it that such a critical item slipped their minds? We argue that vulnerability to such errors is not an indication of lack of expertise, but rather a function of the way normal human memory processes operate in situations involving routine, well learned behaviors.

Most memory errors we experience in our everyday lives fall into one of two basic categories. The first category involves situations in which we attempt unsuccessfully to retrieve information from memory. Forgetting where we left the car keys, the name of a new restaurant or how to knit a sweater, all fall into this category of *retrospective memory* errors. Much of the variance associated with retrospective memory performance is a function of the level of learning or exposure (e.g., Baddeley, 1990). The more often we have encountered or rehearsed information in the past, the more likely we are to be able to retrieve it in the future. We are less likely to forget the name of a restaurant we have frequented many times than one we visited only once.

The other type of memory error involves forgetting of intentions. Forgetting to bring your lunch to work, to pick up the dry cleaning or to attend a meeting, are all instances of *prospective memory* failures. Prospective memory shares many of the basic cognitive features that underlie retrospective memory but differs in important respects, namely prospective memory not only requires retrieval, but also requires that retrieval occur *at the particular moment* when the intention is to be performed. If the individual is not deliberately searching memory for the intention, how is it retrieved—how does one remember to remember?

Research to date suggests that much of the variance in prospective memory performance is attributable to the mechanisms by which retrieval is initiated: *cueing* and *attention* (e.g., McDaniel & Einstein, 2000). Retrieval of intentions often occurs when the individual encounters a cue or prompt. To be a good reminder a cue must have two features. First, it must be highly associated to the specific intention such that it has a high probability of calling that intention to mind when it is noticed. Second, the cue must be salient, or have a high likelihood of being noticed at the time that the intention must be performed. Thus a ground proximity warning that annunciates "Gear, Gear" is a good cue to remind pilots who have forgotten to lower the landing gear; this cue is both specific to an intention and salient enough to reliably capture attention.

The cockpit environment does not always provide pilots with cues as salient as a gear warning.

Monitoring and attention become essential when cues are less noticeable. The less likely a cue is to capture attention, the more we must monitor for its occurrence (e.g., Einstein, McDaniel, Richardson, Guynn, & Cunfer, 1995). The more attention we direct to a cue, the more likely we are to recall the associated intention (e.g., West & Craik, 2001).

The risk of prospective memory errors is greatly reduced when aviation operations are strictly proceduralized and overlearned. If tasks are consistently performed in the same sequence and under the same circumstances, the context begins to provide cues that prompt pilots to perform each task. For instance, items in the preflight procedure flows are less likely to be forgotten because they are routinely performed in the same order and at the same stage of preparation. Performing the first item of a flow is a reliable cue to perform the second item, which in turn is a cue to perform the third item, and so on. This is extremely useful to pilots in that it both reduces the need to devote attentional resources to recalling each item, and reduces the likelihood of forgetting an item, so long as the routine is preserved. However, this reliance on predictable cues has a downside in that it may also make those same items more vulnerable to forgetting when the normal cues are not available, such as when the procedural flow is interrupted or pilots must perform an action out of its normal sequence (Loukopoulos, Dismukes & Barshi, 2001).

We analyzed a set of reports made to the Aviation Safety Reporting System (ASRS) in order to develop a better understanding of cockpit memory errors. Although reports submitted to the ASRS are voluntary and therefore do not necessarily offer a representative or comprehensive picture of cockpit operations, these reports do provide valuable information about many of the types of memory errors to which pilots are vulnerable and the circumstances that contribute to those memory errors.

Analysis

Using the ASRS searchable database we extracted a random sample of 20% of all reports involving part 121 operations submitted during 2001. Each of 1299 reports was read and analyzed to determine whether the incident involved a memory failure. One hundred and five (8%) were identified as examples of memory errors (this is probably a substantial undercount as many reports did not include enough information to evaluate the possible presence of memory errors). Thirty of these reports indicated maintenance or controller errors and 75 indicated memory errors by pilots. The first two authors then discussed and categorized the 75 reports involving memory failures committed by pilots, considering both operational and cognitive factors.

Only one of the 75 memory reports described an instance of a retrospective memory failure (the crew recalled another crew's clearance instead of their own). The remainder involved some form of prospective memory failure (Table 1). The low incidence of retrospective failures may seem surprising. However, most normal cockpit tasks are so overlearned that experienced pilots may rarely experience retrieval failures - a seasoned aviator is not likely to forget how to program the flight management computer or how to lower the landing gear. Furthermore, much of the declarative information that pilots must remember is available in the cockpit (e.g., communication frequencies on instrument approach plates) if a pilot searches for a forgotten item.

We categorized the 74 reports involving prospective memory according to four themes: monitoring, absence of cues, habit capture, and poorly formed intentions. These are not exclusive categories, and many reports involved more than one theme. We assigned each report based on the factor that appeared to have the greatest influence on the pilot's behavior during that incident.

Table 1
Number of errors per category

Forgot to monitor	19 (26%)
Absence of adequate cues	27 (36%)
Habit capture	14 (19%)
Poorly formed intentions	14 (19%)
Total	74

Monitoring

Of the 74 reports, 26% involved forgetting to adequately monitor for the appropriate moment to perform an intention. These errors resulted in some sort of course deviation, such as an altitude bust or a failure to make a crossing restriction. Attention processes are obviously central to monitoring, but initiating and maintaining monitoring also involves memory retrieval. Periodically retrieving the intention to monitor is itself a prospective memory task.

> Shortly after takeoff...the flight director failed, followed by the flight guidance panel going totally inop...The captain (pilot flying) asked me to switch flight director to 'both'...while I

> was locating and changing the position of the switch we passed through our clearance altitude... (Accession # 486880).

In this example, task demands related to the abnormal situation diverted the first officer's attention from monitoring altitude at a critical moment. Several recent studies have addressed cockpit monitoring issues (e.g., Dismukes, Young & Sumwalt, 1998; Sumwalt, 1993; Sumwalt, Thomas & Dismukes, 2002), so we will focus here mainly on the other three prospective memory error themes.

Absence of Cues

Memory failure in 36% of the reports appeared to be caused primarily by a lack of adequate cues. Standardization of cockpit operating procedures generally protects against this type of error by providing consistent, highly effective cues for most tasks. However, when the routine changes such that those cues are no longer available or attention is diverted from those cues, pilots become quite vulnerable to forgetting to perform the task.

Thirteen (18%) of the reports involved situations in which a flightcrew landed without clearance. In normal operations the crew switches from the approach controller frequency to the tower controller who eventually provides a clearance to land. In all but one of these reports the memory error occurred when the crew forgot to switch frequencies and call the tower controller.

> We landed and taxied clear of the runway. However, apparently the FO had not received a clearance to land. Our radio was still on the approach frequency (Accession # 493970).

Certainly the pilots submitting these reports intended to contact tower and to receive clearance before landing. Transferring to the tower controller and obtaining a clearance is part of a well-practiced routine. So why are pilots vulnerable to forgetting this particular intention? The answer may lie in the type of instructions that the crews received from ATC in these instances.

> Approach told us to switch to tower at the final approach fix. (Accession # 472320)

> Clearance was to …contact tower at the marker. (Accession # 468770)

Typically, approach control directs crews to switch to tower immediately. However, in these examples the crews were instructed to switch at some later point in time. In this situation a salient cue was provided (the instruction from approach) but it occurred well before the window of opportunity for performing the task. The intention to switch to tower was probably retrieved but dropped out of awareness before the pilots could initiate the task. Research has found that people are vulnerable to forgetting to execute an intention when they are required to delay execution even a few seconds after receiving the cue for execution (Einstein, McDaniel, Manzi, Cochran & Baker, 2000). This effect is even greater when subjects are busy, as crews certainly are during an approach and landing. Although other cues may be available when the switch to tower is supposed to be made (e.g., at the outer marker) these cues are less likely to be noticed than a call from the controller. Even if these other cues are noticed they are less strongly associated with, and therefore less likely to prompt, retrieval of the intention to switch to tower. Receiving an immediate hand-off is an excellent cue for switching to tower because it is very likely to be noticed and is very likely to call to mind the appropriate action. The fact that it is an effective cue means that pilots are likely to rely on it, making them more vulnerable to forgetting in the few instances when it is not available.

Interestingly, in most of these reports the pilots noticed their error shortly after landing. Landing is an effective and reliable cue to transfer to ground control. Upon receiving this cue the pilots started to switch their radios to ground control and only then realized they were still on the approach frequency.

Once a flightcrew progresses beyond the point at which they normally switch to tower frequency, the crew becomes less likely to note that they have not received a landing clearance. This phase of the approach is highly associated in the pilots' memory with having already received a clearance. The environmental cues are not associated with switching frequencies, and even if the pilots do think about switching they are vulnerable to confusing memory for this instance with their many memories of having received a clearance by this point (e.g., Johnson, Hashtroudi, & Lindsay, 1993).

Another commonly observed error was failing to set or reset the altimeter, which occurred in 6 (8%) reports. Normally pilots change the altimeter from a local setting to 29.92 when climbing through 18,000 feet and then reset it to a local setting when descending through 18,000 feet. Depending on the discrepancy between settings, an incorrect altimeter setting can result in significant altitude deviations. As a result the error is often caught by an air traffic controller who notices the altitude deviation and alerts the crew before it poses a problem. However, in one report, the crew experienced a loss of separation from another aircraft, receiving a traffic alert from the onboard system before recognizing the problem. The pilots making these errors certainly intended to set the altimeter and no doubt performed the task without difficulty on most other occasions. So why do pilots make this error?

This situation may be particularly problematic because the cue to perform the task is not likely to be noticed without vigilant monitoring. Altimeters provide the only direct cue to reaching 18,000 feet. Pilots will not perceive this cue unless they are looking directly at the altimeter. One pilot recognized the need for a more salient cue:

> A flight level 180 check would decrease the possibility of [forgetting to set altimeters] again (Accession # 494067).

We suspect that in most circumstances other activities routinely performed around climb and descent (e.g., briefing the approach) remind the pilot to monitor for 18,000 feet, and the correct moment to set the altimeter. However, when that monitoring is disrupted the pilot becomes vulnerable to forgetting.

> It was moderately turbulent during our descent…. We were distracted at this time and failed to reset our altimeters to the new…setting (Accession # 468640).

Habit Capture

A second major category of errors (19%) involves instances in which the pilot performed a habitual task instead of the intended task. In these situations pilots intend to substitute an atypical action for a habitual action normally performed in the situation, but forget and revert to habit. Although the atypical intention is presumably "fresh" in memory, it must compete with the habitual intention for retrieval. The overlearning that protects habitual actions against forgetting during routine operations makes pilots vulnerable to error particularly when they are busy, fatigued, or interrupted. Cues for habitual tasks are so effective that they often initiate behavior automatically unless deliberate effort is made to inhibit the habitual response.

Many of the reports in this category describe instances in which the crews were very familiar with an airport and the approaches and departures around it. Even though they acknowledged a new instruction and presumably encoded the appropriate intention they performed a habitual action instead.

> Our error was continuing on J174 past ZIZZY toward SWL…. We fly J174 to SWL 3-4 times per week and simply forgot we had received a change to our planned flight plan (Accession # 487740).

We suspect that if someone had asked this crew to state their flight plan they would have described it correctly. However, the flow of events was more strongly associated in memory with the habitual flight path than with the atypical plan and triggered the wrong actions. In highly familiar situations people tend to respond automatically with habitual actions, rather than thinking explicitly about each action, which requires much more mental effort. For this crew, being on J174 triggered the habitual intention to continue to SWL, despite the changed flight plan. In contrast, there were no salient cues to remind the pilots to follow the new clearance. If the pilots had reminded themselves of the new clearance periodically, they might have had a better chance of remembering to perform the correct action, though they would still have been somewhat vulnerable because habitual responses are difficult to inhibit.

In some instances the crew should have inserted a new intention among a series of habitual intentions.

> Departed…with open logbook item. Departed early and in the last minute forgot the item was not signed off by maintenance (Accession # 474050).

As in the previous example several factors probably contributed to this particular memory failure. Because resolving the logbook item was not a routine task no cues in the normal procedures were associated with this task; there were no effective prompts for that task. Also, the pilots would have had to disrupt their normal flow of activity at some point before pushback in order to initiate this task. It is difficult to remember to interrupt a procedural flow that is routine and overlearned because each step of the habitual flow strongly triggers the next step.

In this sort of situation active monitoring for an opportunity to perform the task can reduce vulnerability to forgetting. These pilots would have been less vulnerable if they had been actively searching for an opportunity to resolve the logbook item. However, monitoring requires attentional resources. During busy moments those resources are in high demand and monitoring processes are likely to suffer (e.g., Kliegel, Martin, McDaniel & Einstein 2001). The reporter in the above example mentioned that they departed the gate early, suggesting that they may have been rushed and busier than usual, and as a consequence may have had fewer resources available for monitoring.

Poorly Formed Intentions

From our theoretical perspective, in the absence of continuous monitoring, successful retrieval of a new intention relies on processing that occurs when an intention is formed. This processing, or *encoding*, of an intention involves establishing a plan for retrieval by linking the intention in memory to specific cues that the individual is likely to encounter in the environment when it becomes appropriate to execute the intention (Nowinski & Dismukes, in press). Although encoding is generally a mental task, it can also involve creating a physical cue such as tying a string around one's finger. Some pilots take time to encode important intentions and increase the probability of retrieval by creating cues that are likely to be noticed, such as placing a checklist between the throttles as a reminder to execute an intention before take-off. Deliberate encoding of intentions may be especially critical in the cockpit, where, as we have discussed, new intentions must often compete with highly practiced tasks.

In 19% of the reports we inferred that poor encoding contributed to forgetting to perform an intention. Poorly formed intentions probably also contributed to other memory errors listed under other categories. For instance, poor encoding of new intentions decreases the probability that those intentions will be able to compete with habitual tasks.

In most of the reports involving poor encoding, the pilots were confronted with situations that required a series of actions; the pilots completed the first task, but failed to perform all of the subsequent necessary actions.

> We began taxiing to runway 28.... Ground control informed us runway 28 was now closed and to make a 180 degree turn back to runway 24R…. When reaching the departure end of 24R, we were cleared for takeoff. At 400 feet…heading select [was] incorrect for runway 24R, but correct for runway 28, our original runway (Accession # 494810).

The pilots reporting this error were faced with multiple tasks upon receiving their new runway assignment, including reprogramming the FMS and amending their input to the heading selector. If asked these pilots would probably have said that they intended to change the setting in the heading selector so that it was correct for the new runway. Yet they may never have encoded that intention explicitly. Preparing the aircraft during the preflight flow, when the heading selector is normally set, provides good cues for remembering. Changing runways during taxi is an atypical procedure, and potential cues for resetting the heading selector are therefore not well established in memory and are less reliable. Retrieving an intention outside of its typical context is left to chance reminders unless pilots deliberately re-encode the intention, explicitly identifying potential cues.

In other instances the pilots took the time to form a new intention but failed to identify an effective cue.

> Turned on both center pumps to deplete approximately 800 pounds [of fuel]. Started clock to estimate time to turn off pumps. Briefly discussed maximum altitude aircraft was capable of obtaining with moderate turbulence…. After verifying flight level 410 was acceptable looked up and noticed the center tank fuel had just reached zero pounds and turned off pumps (Accession # 469100).

The reporter recognized the possibility of forgetting the fuel pumps while engaged in other tasks. The pilot decided to create a cue as a reminder of the intention to turn off the pumps after 800 pounds had been depleted from the center tanks. However, the clock was not an effective reminder. The pilot may have been successful at associating the clock with the intention but the clock did not draw attention at the moment when the intention should have been performed. The clock would have been a more effective cue if it had included an alarm feature or if the pilot could have placed it in an unusual position where it would be unlikely to escape notice.

Conclusions and Potential Countermeasures

The occurrence of only one retrospective memory error in 75 reports of memory failure is an interesting finding though not surprising. Airline training, operating procedures, cockpit design, and cockpit documents help support retrospective memory. Some support is also provided for prospective memory. Checklists help pilots detect omission of "killer" items, and the pilot not flying can monitor some of the actions of the pilot flying. However, this study suggests that current defenses are less effective against prospective memory errors than against retrospective memory errors. (See also, Dismukes et al., 1998 and Loukopoulos et al., 2001). Also of interest are the four categories of errors that emerged during our analysis: monitoring, absence of cues, habit capture and poorly formed intentions. We suspect that these categories are not specific to aviation operations but rather reflect the nature of prospective memory performance and the difficulties inherent in retrieving delayed goals in complex real world situations.

One common denominator among all of the memory errors observed in these reports is that they might have been avoided if the pilots had been able to devote more attention to the forgotten tasks. Monitoring for opportunities to perform a deferred task reduces dependency on happenstance cues to trigger retrieval of an intention. However, attention is a valuable and limited resource in the cockpit, and often pilots divert attention to perform concurrent tasks. Many of the reports we reviewed described errors that occurred during atypical operations. These situations often result in both less time for monitoring and the disruption of normal procedures, which undercuts the cueing that normally supports memory retrieval.

What countermeasures might reduce vulnerability to prospective memory errors? Given what we know about successful prospective memory performance we can make some tentative suggestions:

1) Recognize non-routine situations, namely interruptions, deviations from habitual actions, and deferred tasks, as potentially dangerous. If possible identify exactly when a deferred or interrupted task will be performed and what cues will be available. Create salient cues as reminders. If possible enlist the help of other crewmembers. At the very least, acknowledge the fact that a task is being deferred.

2) Stick to established operating procedures as much as possible—they provide both obvious and subtle safeguards against forgetting.

3) Recognize monitoring as a critical task. Several airlines have formalized monitoring procedures for both pilots and have changed the designation of pilot not flying to pilot monitoring (Sumwalt et al, 2002).

Acknowledgments

Funding for this work was provided by NASA's Aviation Safety Program.

References

Baddeley, A. (1990). *Human Memory: Theory and Practice.* Allyn & Bacon: Needham Heights, MA.

Dismukes, R. K., Young, G., & Sumwalt, R. (1998). Cockpit interruptions and distractions: Effective management requires a careful balancing act. *ASRS Directline*, *10*, 3.

Einstein, G. O., McDaniel, M. A., Manzi, M., Cochran, B. & Baker, M. (2000). Prospective memory and aging: Forgetting intentions over short delays. *Psychology & Aging*, *15*(4), 671-683.

Einstein, G. O., McDaniel, M. A., Richardson, S., Guynn, M. J., & Cunfer, A. R. (1995). Aging and prospective memory: Examining the influences of self-initiated retrieval processes. *Journal of Experimental Psychology: Learning, Memory, & Cognition* ,*21*(4), 996-1007.

Johnson, M. K., Hashtroudi, S., & Lindsay, D. S. (1993). Source monitoring. *Psychological Bulletin & Review*, *114*, 3-28.

Kliegel, M., Martin, M., McDaniel, M. A., & Einstein, G. O. (2001). Varying the importance of a prospective memory task: Differential effects across time- and event-based prospective memory. *Memory*, *9*(1) , 1-11.

Loukopoulos, L. D., Dismukes, R. K., & Barshi, I. (2001). Cockpit interruptions and distractions: A line observation study. In R. Jensen (Ed.), Proceedings of the 11th International Symposium on Aviation Psychology. Columbus, OH: Ohio State University.

McDaniel, M. A. & Einstein, G. O. (2000). Strategic and automatic processes in prospective memory retrieval: A multiprocess framework. *Applied Cognitive Psychology*, *14*, S127-S144.

National Transportation Safety Board (1988). *Aircraft Accident Report* (NTSB/AAR-88/05). Washington, D.C.: U.S. Government Printing Office.

National Transportation Safety Board (1989). *Aircraft Accident Report* (NTSB/AAR-89/04). Washington, D.C.: U.S. Government Printing Office.

Nowinski, J. L. & Dismukes, R. K. (in preparation). Prospective memory: A theoretical framework.

Sumwalt, R. (1993). The sterile cockpit. *ASRS Directline, 4*.

Sumwalt, R. L., Thomas, R. J., & Dismukes, R. K. (2002). Enhancing flight-crew monitoring skills can increase flight safety. Presented at the 55th International Air Safety Seminar, Flight Safety Foundation, Dublin, Ireland, November 4 - 7.

West, R. & Craik, F. I. M. (2001). Influences on the efficiency of prospective memory in younger and older adults. *Psychology & Aging* ,*16*(4) , 682-696.