Chapter 5

Analysis of Concurrent Task Demands and Crew Responses

It is clear from the last chapter that actual flight operations are much more complex than portrayed by FOMs. The ideal flow of procedures is constantly perturbed by events and task demands; consequently, cockpit work is in reality dynamic, semi-predictable, and only semi-controllable. Even routine flights require pilots to deal with multiple task demands concurrently by improvising, rearranging, and interleaving planned tasks with unexpected tasks. But so what? In the 60 flights that we formally observed, the crews dealt with many diverse perturbations effectively and with aplomb. Questioned during the Cruise phase or after the end of the flight, pilots reported not having found the perturbations to be in any way extraordinary or threatening. Some were consciously aware of having experienced and addressed multiple perturbations but casually regarded this as "business as usual." Others were so inured to concurrent task demands that they seemed not to recognize that perturbations had occurred and, knowing the purpose of our presence in the cockpit, expressed disappointment that "nothing interesting" had happened.

Consider, however, the following report submitted to NASA's Aviation Safety Reporting System (ASRS) database by the captain of a Boeing 737:

> "As we pushed back, I noticed a lengthy line of aircraft waiting for takeoff at our anticipated runway, which was just a short distance behind us. I made a decision to just taxi the short distance on one engine [engine #2]. This break in our normal flow was distractive enough that I didn't call for flaps. Ground Control then assigned us a different, distant runway with more complicated than normal instructions… Still anticipating a wait at the end, I continued taxiing on one engine. During the taxi, we continually evaluated the heavy rain showers we would encounter on our departure… We stopped at the end of the parallel [taxiway] and Ground sent us to Tower. Tower told us to pull up [#1 in line]. We started the second engine and with rollback [of engine indications], I started moving immediately fearing delay might make ATC change their mind about us being next. Again, the break in flow resulted in not calling for takeoff flaps. We continued scanning the weather as we moved ahead and turned, running the checklist. The combination of doing these things resulted in passing through the flaps item on the checklist without confirming their position. We were cleared for departure and as I pushed the throttle up we got 2 chirps from the takeoff [configuration] warning horn."
>
> (ASRS report # 519061)

(Note: all ASRS narratives have been edited and text in brackets has been added for clarification. ASRS reports can be accessed online at http://asrs.arc.nasa.gov/.)

The takeoff configuration warning horn sounds if the throttles are advanced when the aircraft is on the ground and not properly configured for takeoff.[1] In this incident, the flaps had not been extended as required for safe takeoff, but the flight was saved from disaster by the warning system. In at least one other case, however, the same warning failed to sound and the crew attempted to take off, crashing shortly after starting to climb (NTSB, 1988).

Pilots reporting close calls such as in the ASRS report above are usually shocked that they could have made such a potentially catastrophic mistake, but typically attribute the oversight to a momentary loss of vigilance and resolve to "be more careful" in the future. However, we argue that pilots underestimate their own vulnerability to errors of omission and that checklists and other safeguards against inadvertent omissions are themselves vulnerable to error. In this chapter, we discuss the kinds of error associated with typical concurrent task situations arising from the types of perturbations we described in the previous chapter and analyze the task demands and cognitive processes underlying the vulnerability to errors of omission. This analysis lays a foundation for developing countermeasures to reduce this vulnerability, discussed in the final chapter.

Between 1987 and 2001, 27 major airline accidents occurred in the United States in which crew error was found to be a causal or contributing factor (Dismukes, 2006). In five of these accidents, inadvertent omission of a normal procedural step by pilots played a central role (NTSB 1988, 1989, 1995, 1997, 2001). Two accidents involved failing to set flaps and slats to takeoff position. The other three involved: failing to set hydraulic boost pumps to the "high" position before landing, causing the landing gear to not extend on command; failing to turn on the pitot heat, causing erroneous airspeed indications on takeoff (Flight 795, mentioned at the beginning of this book); and failing to arm the spoilers before landing, which combined with other errors and a wet runway to prevent the airplane from stopping before the end of the runway. A striking feature of each of these accidents is that, not only did the crew forget to execute a normal procedural action they had performed on thousands of previous flights, they also failed to catch the omission when later performing the checklist designed to ensure completion of this and other crucial procedural actions.

In a detailed analysis of the 19 major U.S. airline accidents attributed primarily to crew error in the decade between 1990–2001, Dismukes and his colleagues (2007) found that concurrent task and workload issues appeared explicitly or implicitly in the great majority of those accidents. In some, workload and time constraints were quite high in the final stages of the accident sequence, but in many others adequate time was available to perform all required tasks. In this

1 In older versions of the Boeing 737, the takeoff configuration warning horn sounds as a function of flaps not having been set for takeoff and EPR (exhaust pressure ratio) reaching a certain setting.

latter group of accidents, it appears that crew performance was undercut by the cognitive difficulties inherent in reliably switching attention back and forth among concurrent tasks and in remembering to perform tasks that must be deferred out of normal sequence. This analysis found no evidence that the errors in these accidents could be attributed to deficiencies in the skills of the pilots—they were all highly experienced and appeared to be representative of the general population of airline pilots.[2] Thus, it appears that errors of omission largely associated with diverse aspects of concurrent task management, when not detected and corrected, are a major threat to aviation safety (also, see Dismukes et al., 1998).

Considering the intrinsic threats posed by frequent perturbations and concurrent task demands, why were the crews we observed so nonchalant about managing these situations? The first explanation is probably that pilots develop considerable skill responding to routine perturbations, and become adept at juggling concurrent tasks, integrating unplanned new tasks, and rescheduling tasks. Judging from the outcome of the flights observed, pilots appear to handle these situations without error most of the time, and when errors occur they are usually caught before propagating into an accident or even a frightening incident.[3] Second, many of the cockpit tasks experienced pilots perform are highly practiced and over time

> On an early afternoon in January, an EMB145 aircraft had been flown with the pressurization system in the manual mode after a suspected leak of the service door. The necessary maintenance work was deferred, as per procedures, until the aircraft got to an airport where the necessary repairs could be performed. In the meantime, the aircraft outflow valves were secured in the open position. When the aircraft arrived at its maintenance base, the technician proceeded with the necessary repair tasks that included resealing the rubber door trim and the lower service kick plate. He logged the accomplished tasks and noted that the pressurization system had been restored. The aircraft was dispatched for flight. In flight, the flight crew discovered that the aircraft could not be pressurized in either the automatic or the manual system modes. Once safely on the ground again, an investigation to determine the cause of the failure of the pressurization system showed the outflow valves still open, in the position they had been secured prior to the maintenance work. At the completion of the earlier maintenance work to restore the system, the technician had forgotten to remove the tool that had been used to keep the valves open.
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> (U.S. Aviation Safety Reporting System, Report # 687117)

2 See Dekker's (2002) criticism of the "bad apple" theory of aviation accidents according to which it is assumed that a complex system would be safe if not for the erratic behavior of unreliable operators—that is, accident pilots are considered deficient and not representative of airline pilots.

3 Data from the last decade show around 15 million aircraft departures are carried out per year worldwide. Yet the 10-year accident rate (fatal accident or hull loss) in scheduled passenger flight operations is less than 1.0 accident per million departures (Boeing, 2007).

become largely automatic and seem not to require substantial mental effort. (This is discussed in depth later in this chapter). Thus, managing several familiar tasks concurrently may not seem challenging. Finally, pilots (not to mention airline instructors, procedures designers, and managers) may be overconfident in the reliability of measures designed to catch errors of omission, in particular when executing checklists and performing monitoring tasks. But execution of checklists is vulnerable to errors of omission for many of the same reasons that steps in procedures are inadvertently omitted. Monitoring also requires clearly-defined processes, discipline, and well-established habits to be effective. (See Dismukes et al., 2007, and Sumwalt, Thomas, and Dismukes, 2002, 2003, for detailed discussion of these issues.)

Still, if the great majority of errors do not propagate into accidents, why should we be especially concerned with them? The main reason is that accident rates are at best an incomplete measure of the level of safety of a system. Accident rates are, thankfully, very low; thus analyzing accidents, though useful, only gives insight into what has happened in the past. And because accidents result from the somewhat random interaction of multiple factors, the small sample available from the history of accidents only partially captures latent vulnerabilities lurking in the system that may interact to produce new accidents.

Collecting data on errors provides a much larger and more representative sample of latent vulnerabilities. Error data can be obtained from several sources, for example:

1. Direct observation of flight crews performing in line operations, as we have done in this study, and in LOSA (Line Operations Safety Audits),
2. Flight simulation, in which direct observations can be supplemented by video, audio, and flight data recordings, and extensive de-briefings of pilots, and
3. Incident reports from pilots and other personnel, as provided to the ASRS and to similar report databases that are kept by individual airlines as part of their Aviation Safety Action Programs (ASAP).

LOSA data indicate that even on completely routine flights most crews make at least one error (FSF, 2005; Helmreich, Klinect, and Merritt, 2004). But it is not sufficient to just identify and perhaps categorize errors. To determine how errors affect the safety of the aviation system, one must examine the circumstances in which errors occur (including task demands, events, and organizational factors), the cognitive processes underlying each type of error, and the ways in which pilots typically respond or fail to respond to various types of error—which is what we attempt to do in this book. This type of analysis lays a foundation for devising practical ways to reduce system vulnerabilities.

Our ASRS Study

To explore how the kinds of perturbations observed in our jumpseat study might affect pilots' vulnerability to error, we conducted a search of the ASRS database.[4] This database consists of several hundred thousand reports voluntarily submitted by pilots and other aviation personnel about incidents in which safety was potentially compromised. These reports, many of which identify errors made by the reporting individual, briefly describe an incident, the surrounding circumstances, and any insight the reporter may have to offer on why the errors were made. We used a guided search technique to identify reports describing errors associated with the kinds of perturbations we observed from the cockpit jumpseat, using the events and the surrounding circumstances as search terms. (See Appendix A for more details on our study methods.) For example we found that runway changes during taxi often presented crews with multiple additional task demands that had to be integrated with normal tasks, so we used "runway change" as one of the search terms. In this fashion, we identified reports of pilot errors associated with perturbations similar to those we observed from the cockpit jumpseat. Appendix D briefly summarizes the perturbation ("Perturbation source") and the resulting error ("Consequence") reported in each incident. Although this list is far from exhaustive, it is representative of the reality of line operations, and the perturbations are quite similar to those we personally observed.

Scanning this list, it is clear that the nature and timing of the perturbing events was quite variable, ranging from a momentary interruption while the crew was performing a checklist to the attention-consuming demand of maintaining visual contact with traffic while making final landing preparations. The consequences of these perturbations also varied in nature and severity, mostly leading to errors of omission, some of which were noticed immediately, before generating an undesired situation, and others only after the error caused a subsequent problem. The amount of time before these problems became apparent varied greatly (e.g., one pretakeoff error had immediate consequences, while another did not become apparent until the flight reached cruise).

We have selected four of these incidents to illustrate how perturbations can increase pilots' vulnerability to error. Multiple factors undoubtedly played a role in each of these incidents, but clearly the perturbation was a central factor.

> "After takeoff from ATL [Atlanta airport] and climbing through 16,000–17,000 ft, the flight attendant called and inquired as to seat belt, rough ride, thunderstorms, etc. This got us both occupied and I forgot to do the Climb checklist, thus

4 De-identified ASRS data are publicly available in a form that can be readily searched, which is one reason we used this source of error data. LOSA data and ASAP data, which provide a rich and complementary source of data, are unfortunately not available to most researchers.

> missing [setting the] altimeter setting [to] 29.92.[5] The rest of the climb was done in steps, i.e., as we approach FL240 we were given FL260, etc. After level-off at FL350, ATC asked us to check our altimeter for 29.92. Ours were set at 29.61, thus making us 250–300 ft high."
>
> (ASRS report # 394580)

The perturbation in this incident resembles the one discussed in the last chapter under "visitor" in which the flight attendant entered the cockpit just as the crew received a new instruction from the air traffic controller. In the "visitor" incident the crew we observed from the jumpseat chose to motion the attendant to wait for them to respond to the controller first. However in the incident described above the flight attendant called from the interphone, so it was not possible to signal the attendant to wait. Although this crew could have ignored the interphone temporarily they chose to respond immediately, but the ensuing conversation diverted attention at a time when the crew had been about to initiate the Climb checklist. The habitual flow of activities was disrupted and the crew forgot to execute the checklist and consequently failed to reset the altimeters to 29.92 inHg, as required at 18,000 feet of altitude. This example illustrates that when pilots are interrupted, their attention is diverted at least momentarily. They must then decide whether to suspend the ongoing task to address the interruption and then return to the suspended task, or to defer addressing the interruption until a more opportune time. In either case, pilots must remember to perform a deferred intention, which is an example of a prospective memory task. Later in this chapter we discuss the cognitive processes involved in prospective memory and analyze why these processes are sometimes vulnerable to errors of omission.

> "We were tired due to a long day with delays, we had a change and were told to fly [the aircraft] instead of ride [as passengers, back to the home base] and we now had to rush over to the other side of the airport and hurry and takeoff. The preflight checks were rushed, we had to be deiced and there was packed ice and snow on the taxiways. With these icy conditions, our company procedure is to taxi out with the flaps up to prevent ice accumulation on the flaps, then set the flaps to takeoff position right before takeoff. This is a major change from our normal flap procedure. The Before Takeoff checklist was recently changed… The flap position check is now the first item on the Before Takeoff checklist (which is done while taxiing out) and is never checked again. As we taxied out for takeoff, I ran the checklist and left the flaps up as per the cold weather procedures. I informed the captain of this. As we approached the runway for takeoff, Tower asked us if we were ready, we said 'yes,' and they cleared us for immediate takeoff. The checklist then leads you to check the 'final items' as

5 See section *Takeoff, Climb, and Cruise* in the Ideal chapter for a brief explanation of the altimeter setting procedure.

> you take the runway. These final items do not include another check of the flap position. I said 'checklist complete,' the captain advanced the throttles to takeoff power setting, and we got the takeoff warning horn. It was at this point that we realized that we had attempted to takeoff with no flaps—a potentially fatal error. We aborted the takeoff, reset the flaps, and took off."
>
> (ASRS report # 263325)

(As discussed in the Taxi phase description in the Ideal chapter, the checklist to be executed prior to takeoff is often separated into two parts—the first is conducted soon after the beginning of taxi, while the second, "final items," is conducted right before takeoff, as soon as takeoff clearance is granted.)

This incident closely resembles the situation described under "call back later" in the last chapter, in which the first officer was busy with other tasks when the captain was ready to ask for the checklist. In that case, the captain was forced to defer the checklist but successfully remembered it later once the first officer became available. In the current incident, the crew was forced to defer setting flaps to takeoff position, and then forgot to complete that essential task. Crews normally perform cockpit tasks in the sequence prescribed by the FOM, and the many repetitions of the sequence of actions in these tasks causes performance to become automatic and normally quite reliable. But on occasion, situational factors or the unavailability of another person or of needed information require the crew to defer performing a task out of the normal sequence. For reasons that will be explained, this task deferral greatly increases vulnerability to forgetting to perform the task—yet again, a prospective memory task that may lead to errors of omission.

> "I picked up a clearance from LGA [La Guardia airport controller] which was to 'taxi to runway 4 via taxiways A, F, B, hold short of [not cross] taxiway E.' After reading the clearance back, we were told to contact Clearance delivery for a change to the routing [a change to the en-route instructions to follow after takeoff]. I then stated to the captain our taxi clearance and said 'I am off on com #2, you have com #1.' I left the Ground frequency and proceeded to pick up our new clearance while the aircraft was taxiing. When I returned to com #1, I heard Ground state that we were told to hold short of taxiway E. Our position was just short of taxiway D which is south of taxiway E. At this point, the captain stopped the aircraft and asked Ground 'are we clear now to taxi to runway 4?' The answer was 'affirmative' and we continued taxi to runway 4. At no time were we in conflict with another aircraft. The biggest contributing factor to crossing over taxiway E when told to hold short was I was copying the second full route clearance while we were taxiing."
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> (ASRS report # 438470)

(Pilots can use either of the two VHF radios on board by using a switch to select between the two, as necessary. Standard procedure is to set those frequencies they know they will need during each phase of flight on one radio. If the need arises, as it did in this instance, to use a frequency not on the primary radio, the pilot responsible for communications will often temporarily switch to use the second radio. Here, when the first officer announces "going off" one radio, he is essentially informing the captain that he will be switching to the required frequency to pick up the new clearance on the other radio. When one pilot "goes off" one radio or one frequency, the other pilot becomes responsible for monitoring it. Here, when the first officer "goes off" the Ground frequency, the captain becomes responsible for monitoring it.)

The crew in "eavesdropping" in the last chapter was unexpectedly forced to integrate monitoring the situation on the ramp with their preflight duties, which they did, successfully. The crew in the present incident was not so fortunate. The pilots inadvertently violated the controller's instruction to hold short of (not cross) taxiway E on their way to the runway. Although the captain taxiing the airplane committed the primary error (for reasons that cannot be determined from the report narrative), the first officer also made an error by failing to monitor taxi progress so as to catch the captain's mistake before he had crossed taxiway E. The requirement to contact Clearance delivery for a change in flight routing was unexpected, and the first officer had to integrate switching frequencies and copying the revised clearance with his pre-existing, normal responsibility to monitor taxi progress. Unfortunately his attention was absorbed by this unexpected task, compromising his performance in monitoring the taxi. Switching attention between tasks, especially when one of them is a monitoring task and less structured than other tasks, is more vulnerable to error than is commonly recognized. As is discussed later in this chapter, humans in this situation often become absorbed in one attention-demanding task and forget to switch attention periodically to the monitoring task—yet another manifestation of a prospective memory task vulnerable to omissions.

> "We were between 12,000 ft and 11,000 ft MSL on descent, preparing to accomplish the final items on the Approach checklist—1) cycling [momentarily turning off, then immediately back on] of the no smoking sign, our company's method of informing the flight attendants to have passengers stop using personal electronic devices and landing imminent, and 2) recheck altimeters, while being vectored for a visual approach to runway 26R. We had slowed the aircraft to 250 KIAS because we had previously been cleared to descend to 7,000 ft. We were then instructed to proceed to the FAF [final approach fix], descend to 2,500 ft, look for our traffic (a heavy jet), look for traffic turning in for the south runway, and also advised that we had a high overtake speed on our traffic. We accomplished all of those instructions and began to slow and configure the aircraft for landing. We proceeded to accomplish a normal landing. Throughout our entire descent and approach we had been instructed to maintain best forward airspeed. While deplaning the passengers, we were informed… that we had not

> cycled the no smoking sign. Apparently amidst the confusion and distractions from the checklist while being given the short approach we had not cycled the sign."
>
> (ASRS report # 437750)

Like the crew facing the "everything changes" situation in the previous chapter, the crew in this incident was busy with multiple duties while flying the final stages of the approach. Unlike the crew of "everything changes" that successfully accomplished their duties, this crew forgot to signal the flight attendants that landing was imminent. A careful task analysis would show that the flight crew had to constantly switch attention among several concurrent tasks during this busy period. In these situations, it is easy for attention to become absorbed in one or more tasks, allowing another task to drop from awareness. The previous example illustrated how monitoring, perhaps because it is less structured, is particularly vulnerable to being dropped—this example shows that even habitual, well-practiced, structured tasks such as checklist items are not impervious to being forgotten when attention must be shifted back and forth among multiple tasks.

In the four ASRS incidents used here to illustrate the potentially hazardous effects of operational perturbations, no serious harm resulted. The error was either revealed by an external source (e.g., a controller, a warning device), or fortuitously did not combine with other factors to cause harm. However, the potential for harm was present in every one of the illustrated instances. The aircraft could have leveled off at the wrong altitude to find itself in the path of another aircraft, had it continued with an error in its altimeter setting display. The takeoff configuration warning horn could have malfunctioned and not warned the crew it was attempting to takeoff with the aircraft not configured properly. The aircraft could have found itself on a collision course with another aircraft traveling on taxiway E, after having violated the controller's instructions to hold short. The flight attendants might have not finished cabin service and might have still been standing when the aircraft landed. Thus the margin of safety built into the airlines' procedures was substantially reduced by an inadvertent crew error in each case.

Four Prototypical Situations

To develop measures to protect against these sorts of inadvertent errors of omission, we must first understand the cognitive processes underlying performance of tasks involving these diverse perturbations. Skilled performance and the errors made by experts, such as airline pilots, are the two sides of the same coin; because of this intimate relationship, by studying one we gain insight into the other.

Although the perturbations described in this chapter, the previous chapter, and in Appendix D are extremely diverse in their surface manifestations, we identified four distinct patterns running through these examples. We now describe these patterns as four prototypical situations:

1. Interruptions and distractions,
2. Tasks that cannot be executed in the normal, practiced sequence of procedures,
3. Unanticipated new tasks that arise, and
4. Multiple tasks that must be interleaved.

These are not four mutually exclusive categories; rather, they are prototypical situations with both overlapping and distinct features. We organize the discussion in terms of these prototypes both to identify commonalities among these highly diverse situations, and to identify critical features that must be examined to understand why experienced pilots are vulnerable to error in these situations.

Interruptions and distractions

Interruptions occur whenever some event diverts attention from an ongoing task, causing it to be suspended, at least momentarily. Interruptions are so common they may seem unremarkable. Before the cockpit door is closed for departure, crews are interrupted by gate agents, mechanics, flight attendants, jumpseat riders and other individuals who must interact with the crew to perform their own duties. After the door is closed, pilots are interrupted by radio calls, intercom calls from flight attendants, utterances by other crewmembers, and even by their own thoughts that intrude upon attention.

The terms "interruption" and "distraction" are not used consistently in aviation; for our purposes we use interruption to refer to discrete events that must be addressed (e.g., the flight attendant's inquiry about possible thunderstorms, turbulence, and the need to turn the seat belt sign on, as in the first ASRS report above), and use distraction to refer to ongoing conditions that also tend to divert attention but which do not have to be dealt with to accomplish the crew's immediate responsibilities. The content and duration of distractions vary considerably, ranging from a few minutes of non-essential conversation to worrying whether the airline's financial problems will lead to layoffs. Pilots may attempt to ignore unwelcome distractions, such as worrying about being furloughed, that can interfere with performing their tasks, but they may welcome, even invite, other distractions that seem benign, such as casual conversation during periods of low workload. These welcome distractions may help pilots stay alert, especially when fatigued, but all distractions effectively become concurrent tasks that must be interleaved with cockpit duties and which are subject to the problems of interleaving discussed later.

Interrupting events vary greatly in their urgency and in the demands they impose. Being handed a fuel slip by the gate agent may intrude on the first officer's attention for only a few seconds and may not immediately require full attention

> An order for intravenous Diflucan was put though to the pharmacy, to be administered to a man at the emergency department. A mis-labeled bottle indicating "Diflucan" but actually containing Diprivan, a commonly-used sedative-hypnotic, was sent by the pharmacy to the emergency department. The nurse by the patient's bedside waiting for the pharmacy to deliver the Diflucan suspected something awry when she noticed the liquid she received was opaque. She happened to know that intravenous Diflucan is a clear solution.
>
> The nurse decided to question the pharmacy for clarification. Her intention to place a telephone call to the pharmacist was unexpectedly interrupted by a physician's request for immediate assistance with another patient. A few minutes elapsed before she was able to return to the room of the first patient. By that time, she had forgotten her intention to call the pharmacist and proceeded with infusing the IV bag containing the sedative instead of the Diflucan. Less than a minute later the nurse had to attend to the IV because of a problem with the IV pump. It was then that she noticed again the color of the liquid and remembered her forgotten intention to check with the pharmacist. Her prompt intervention to stop the infusion saved the patient from experiencing any adverse effects.
>
> (Agency for Healthcare Research and Quality, 2004)

(i.e., if the first officer has not yet started programming the FMC, which will require him to look at the slip, she can temporarily set the fuel slip aside), whereas being instructed to change radio frequencies during the approach may require the monitoring pilot to immediately interrupt other duties (i.e., monitoring the approach) to devote full attention to entering the new frequency and establishing contact with the next controller. Ongoing tasks also vary greatly in the degree to which they can be interrupted without disruption. Taxiing the aircraft in full visibility at a familiar airport along an uncomplicated route makes few demands on cognitive resources and generally allows the crew to accommodate the interruption of a radio call without difficulty. But programming a complicated route into the FMC, a task that makes substantial demands on cognitive resources, may be seriously disrupted by an interruption.

Interrupting events also vary greatly in their nature and timing, as well as in how predictable they are. Some interruptions, such as the issuance of a revised departure clearance as the crew is approaching the runway for departure and in the process of receiving takeoff clearance, are unexpected, both in content and in timing. Other interruptions, like the transmission of a landing clearance during the execution of an approach, are expected by the crew because they are required for proper execution of the flight. The exact timing and nature of even the expected interruptions, however, is generally unknown and unpredictable. The crew cannot be certain when the landing clearance will be delivered or if it will be delivered at all for that matter—another aircraft on the runway may lead the controller to have to issue a go-around instruction instead of a landing clearance. Nor can the crew predict what tasks they will be performing at the moment the controller's message arrives over the radio. Not knowing exactly when each interruption will occur, or what its nature will be, prevents planning other tasks to accommodate even anticipated interruptions.

Various factors, including the timing and nature of the interrupting events and the nature of the interrupted tasks affect the manner in which interruptions are addressed. For example, powerful, deeply ingrained social rules incline individuals to respond immediately to interruptions presented by another person, either physically present or communicating by radio. Individuals also tend to suspend ongoing tasks immediately to deal with interruptions that can be handled quickly to "get them out of the way."

What is common among diverse forms of interruption is that they divert attention from the task at hand and require the individual to decide whether to suspend the ongoing task in order to address the interruption or continue with the ongoing task to reach a natural stopping point before handling the interrupting event. In either case the individual must remember to perform a deferred task. In the former case the deferred task is the interrupted task; in the latter case the deferred task is responding to the interrupting event. In the section on Cognitive Aspects, we return to the challenges posed by deferring tasks and their link to inadvertent omissions.

Tasks cannot be executed in their normal, practiced sequence

Often, the operational situation may not permit a task to be performed in its normal sequence. For example, the crew in the second ASRS example above was forced to defer setting flaps to the take-off position, normally done before taxiing to the takeoff runway, because company policy required that taxiing in these conditions be done with the flaps retracted to prevent slush from the taxiways being thrown up on the flaps.[6]

In other situations, a task cannot be executed because information or a person expected to supply this information or with whom a task must be coordinated is not available when needed. For example, a first officer may be forced to suspend entering data into the FMC during preflight because the final passenger count has not yet been delivered to the cockpit by the lead flight attendant—the passenger count is a required data point—or a captain may be forced to defer executing a checklist because the first officer is busy with another task at that moment. (Most checklists can only be performed when both pilots are available.)

Deferring one task sometimes forces related tasks to also be deferred. For example, deferring setting the flaps for takeoff necessitates deferring running the Taxi checklist, which includes the flaps as an item to check. This compounds the

6 This was indeed the case with older aircraft, such as the one being flown by the crew in this example from 1994. This requirement does not hold for newer aircraft, as is explained in Chapter Six (The Research Applied).

risk of forgetting to set the flaps because crews may forget to run the checklist for the same reasons they are vulnerable to forgetting to set the deferred flaps before attempting to take off. (The cues that normally prompt execution of the checklist have been removed, and preparations for starting the takeoff occupy the pilots' attention).

When tasks must be deferred, for whatever reason, it is rarely practical to simply wait without performing other tasks until the opportunity arrives to perform the deferred task. For example, when setting the flaps is deferred, the crew must taxi to the runway, accomplishing various other tasks associated with this taxi, before the opportunity to set the flaps occurs. Further, time pressure in flight operations, especially during preparations for departure, is considerable. A crew that delays unduly while waiting for missing information risks losing their departure-time slot and upsetting their passengers. Consequently, pilots typically turn their attention to other pending tasks while waiting for an opportunity to resume the deferred task. Some phases of flight, especially the Taxi phase and the Approach phases, often present a continuous flow of task demands that occupy the crew's attention without pauses that would give the crew a moment to review whether all tasks have been completed. In competition with this continuous flow of ongoing task demands, the crew must attempt to remember at the appropriate time that a previous task was not performed in its normal sequence.

> It was a busy night at the airport. The two maintenance technicians working the overnight shift had two different but time-consuming tasks to accomplish on a B737 parked at a mobile, remote workshop. The aircraft was going to be requiring replacement of its nose wheel spin pads and its toilet dump valve. To complete everything within the allotted time, the two technicians split the tasks. It was 3:30 in the morning when one of the technicians started working on the pad replacement task. He was under time pressure to complete the task so he could assist his colleague and also help another engineer working on a different aircraft. To ensure adequate illumination of the nose wheel area, he used a flashlight which he balanced on the nose wheel strut. While working on the spin pads, he knocked over some tools but rather than interrupt what he was doing, he decided to pick them up after completing the replacement. Later, while picking up the tools he was momentarily distracted by the workshop headlights and forgot his (implicit) intention to retrieve the flashlight from the nosewheel area before departing.
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> The aircraft was subsequently dispatched for flight, following a pre-service inspection. While taxiing to the departure runway, the flight crew found the nose wheel uncontrollable through the rudder pedals or the steering tiller. The flashlight remained stuck in the nose wheel area, unnoticed by the maintenance inspector and by the flight crew, who had conducted two exterior inspections prior to the flight.
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> (U.K. Confidential Human Factors Incident Reporting Programme, Maintenance Error Management System)

Pilots also face challenges when they must remember to substitute an atypical action for one step of a habitual task. For example, on one aircraft type the most frequent flaps setting for takeoff is "five," but under special conditions the crew may have to remember to use a different flap setting. It can also be difficult to remember to *not* perform a normal step of a habitual task. For example, while flying a single engine approach in a particular twin-engine jet (i.e., when one of the engines has malfunctioned or has been shut down for precautionary reasons), the crew may forget to *not* extend the flaps all the way to the normal final landing configuration, rather than only part of the way, as required by the single-engine non-normal procedure. In the section on Cognitive Aspects, we discuss why it is much harder to remember to perform habitual tasks correctly when they must be executed out of their normal sequence or when a step of a habitual task must be replaced or omitted.

Unanticipated new task demands arise

Additional task demands often arise while the crew is executing procedures in the FOM-prescribed manner and sequence. In some situations, the additional task is to be performed at a later time. For example, while the aircraft is descending from 15,000 feet, the air traffic controller may instruct a crew to report passing through 8,000 feet (i.e., to transmit a verbal message to the controller when the aircraft is at that altitude). In this situation the unanticipated task must be added to the existing task requirements, and the crew must integrate it into the normal sequence of activities. The crew must hold the controller's instruction in memory for several minutes while busy with landing preparations, and must remember to retrieve the instruction from memory when the aircraft passes through 8,000 feet. Like an interruption, this situation poses the challenge of deferring a task—in this case a newly added, unanticipated task—and remembering to perform it later.

In other situations the new task must be performed immediately. In the third ASRS example above, the first officer was unexpectedly given instructions for a change to the original routing. At that moment, he was about to begin monitoring the captain who would be starting to taxi the aircraft to the departure runway. Responding to an instruction of this nature must be immediate—the information conveyed redirects what the crew will do next—so the first officer had no choice but to respond to the communication and attempt to integrate the new task it generates with his existing activities. Interleaving unpracticed tasks involving novel aspects with habitual activities is, as we shall see, another challenge that may lead to errors of omission.

Multiple tasks must be interleaved

In many situations pilots cannot defer one task long enough to complete another task and must attempt to interleave the two (or more) tasks. In the fourth ASRS report above, the crew faced a situation in which a routine approach became increasingly complex with multiple tasks requiring attention concurrently: fly the

9 June, 2005, evening, Logan Airport, Boston

Operations at Boston Logan's airport 6 intersecting runways were being monitored by the local east controller (LCE) and the local west controller (LCW) in the Air Traffic Control Tower. That summer evening an Airbus was preparing to make its way to runway 15R for takeoff, under the direction of the LCW. Another aircraft, a Boeing, was intending to take off from runway 9 under the direct control of the LCE. The two controllers were using different frequencies to communicate with the respective aircraft.

Runway 15R intersects runway 9 about 8,000 ft down its 10,000 ft length, so the LCW was required to obtain a release from the LCE in order to give clearance for an aircraft to depart from runway 15R. Accordingly, the LCW instructed the Airbus to taxi into position and hold on runway 15R and when, ten minutes later, the LCE "released" the Boeing for takeoff, the LCW gave the Airbus clearance for takeoff from runway 15R.

Things were proceeding per procedure to this point. Everything was to change five seconds later, when the LCE cleared the Boeing for takeoff from runway 9. That crew applied power and started traveling down runway 9, unaware of the Airbus that was also already headed towards the point of intersection of the two runways. The calm reaction of the Boeing flight crew averted the collision of the two aircraft over the runway intersection.

During the ensuing investigation, the LCE stated that at the time he "released" the Airbus he was very busy coordinating with airplanes and other controllers. Though he did notice the Airbus on its takeoff roll down runway 15R about 1 minute later, he was at that time being distracted by a third aircraft wanting to take off, so he was concerned to keep the traffic moving which, in this case, meant first moving the Boeing out of the way. The concurrent task demands led to his giving clearance to the Boeing for takeoff—but forgetting that the Airbus was still on its takeoff roll on the intersecting runway.

(U.S. National Transportation Safety Board, 2007)

approach with all the component tasks involved, which was made more challenging by the instruction to maintain best forward airspeed (the higher airspeed reduced time available and increased workload), look out for conflicting air traffic reported in the vicinity, and watch out for the aircraft in front, which they were closing on. Each of these tasks made substantial cognitive demands, so it was not possible to perform them simultaneously. In this sort of situation, pilots must switch attention back and forth among concurrent tasks, trying to avoid becoming preoccupied with one task to the neglect of the others. When attention is switched away from one task, that task is momentarily suspended while another task is addressed. However, in contrast to interruptions and deferred tasks, interleaving requires repeatedly suspending one or more tasks momentarily, engaging another task to perform a few steps, then suspending the new task, and re-engaging the previous tasks (or engage a third task) to perform a few more steps of it until all tasks are completed. This type of a situation poses a serious challenge that also sometimes leads to errors of omission.

Cognitive Aspects

From the preceding discussion it is clear that pilots typically respond to the concurrent task demands arising from the various operational perturbations we have described in one of two fundamental ways, either by *deferring* one or more tasks, or by *interleaving* multiple tasks. In some situations pilots may be able to perform multiple tasks more or less simultaneously, but these situations only occur when the tasks are highly practiced together in a consistent fashion, which means that these situations are not really perturbations. Pilots may also employ a strategy discussed in the first chapter and reduce task demands by changing how tasks are performed, either by lowering criteria for quality, accuracy, or completeness of performance, or by deliberately omitting one or more tasks altogether. This strategy may reduce workload in many situations, but in most cases it does not eliminate the need to defer or interleave tasks.

We next examine cognitive mechanisms involved when individuals attempt to respond either by deferring or interleaving tasks. This examination helps us understand why pilots are vulnerable to error in the four prototypical situations of interruptions, unexpected new task demands, tasks that cannot be performed in the normal sequence, or tasks that must be interleaved with other tasks. This discussion of cognitive issues also lays a foundation for ways to reduce vulnerability to error suggested in the final chapter of this book. The three cognitive mechanisms most relevant to the types of perturbation of operations we have been discussing are *prospective memory*, *automatic processing of habitual tasks*, and *attention switching*.

Our analysis is based on what is known about the cognitive processes of individuals, but it is noteworthy that, in the reports discussed above, the second pilot in the cockpit did not catch the first pilot's error. Thus, it is appropriate to consider these errors as crew vulnerabilities, and even more appropriate to think of them as system vulnerabilities, because it is the overall socio-technical system that creates the situations in which individuals and crews are vulnerable to error.

Prospective memory

Suspending or deferring a task with the intention to return to it later, or forming an intention to add a new task at a later time, requires the use of what is called prospective memory. (For simplicity we refer to suspended tasks, deferred tasks, and tasks planned for later execution all as "deferred tasks.") Research on prospective memory is a fairly new field, and much as yet remains unknown;

however, we can outline its general cognitive features (see reviews in McDaniel and Einstein, 2007 and Kliegel, Martin, and McDaniel, 2004).

The individual who wishes to remember to perform a deferred task must form an intention to execute that task when circumstances become appropriate and must retain that intention while attention is directed to performing other tasks. For instance, in the “flaps to go” example of the previous chapter, the completion of the landing checklist had to be deferred until the aircraft was slow enough to allow the flaps to be set to the landing position. The monitoring pilot announced his intention to set the flaps later and to complete the checklist by stating “flaps to go!” He then had to focus attention on various other tasks during the approach while maintaining in memory the intention to set the flaps and to complete the checklist once the aircraft reached the appropriate speed.

Generally, the tasks that are performed while waiting to execute a deferred task make sufficient demand on humans’ limited attentional capacity that the deferred task cannot be maintained continuously in focal awareness and working memory; thus, the intention to return to the deferred task must be retrieved from long-term memory at the appropriate moment. The cognitive mechanisms of retrieval of deferred intentions are the subject of ongoing research, but they are clearly rather fragile, because individuals not infrequently fail to remember to perform deferred actions when the appropriate moment arrives (Guynn, McDaniel, and Einstein, 2001). Research to date suggests that retrieval of intentions from memory requires that the individual notice one or more cues associated with the intention and that the association in memory between the cue and the intention be strong enough to provide sufficient activation for the stored intention to be retrieved back into awareness (McDaniel, Guynn, Einstein, and Breneiser, 2004). In prevalent cognitive theory, “activation” represents the spread of neural activity from one neural circuit to other neural circuits. When a cue is processed in attention, activation spreads from attention to all the memories associated with that cue. In less technical language, these cues act as reminders that help prompt retrieval of intentions from memory.

Several factors greatly influence the probability of an individual remembering at the appropriate moment an intention to perform a deferred task. Ideally, when it is necessary to defer a task, the individual would *encode* that deferral—in other words, make an explicit mental note that the task is to be deferred. Research shows that encoding is most effective when the individual forms an “implementation plan” that specifies when and where the deferred task is to be performed and identifies what the individual is likely to be doing at that time, as well as the environmental cues likely to be present (Gollwitzer, 1999). For example, when it is necessary to defer setting the flaps and completing the Taxi checklist, pilots could explicitly state that they intend to complete these tasks when they reach the runway hold-short line, and encode an explicit intention in memory, so that when they observe the hold-short line it will act as a cue that will help trigger retrieval of the intention from memory.

Not all cues are equally effective. The hold-short line, for example, is a mediocre cue in this case because it is always present at the runway and is associated in memory with all previous flights, and it is especially associated with the tasks that are normally performed as the aircraft turns onto the runway. Noticing the hold-short line is likely to trigger retrieval from memory of goals such as those associated with tasks normally performed when taking the runway, rather than with the goal (i.e., the deferred intention) of setting the flaps and completing the Taxi checklist

Reminder cues are much more effective if they are conspicuous, strongly associated with the deferred task, and positioned in a way that an individual is likely to notice them at the appropriate time (Brandimonte, and Passolunghi, 1994). Also, cues that are distinctive or unusual are more effective than cues that are commonplace or resemble other cues in the environment. If the cue is associated with many memories, then the amount of activation reaching any one of the memories is greatly diluted, something called the "fan effect" (Anderson, 1974). Distinctive or unusual cues have fewer associations in memory and thus spread more activation to relatively few related intentions stored in memory. Conspicuous cues are effective because they are more likely to be noticed and processed with adequate attention. Thus, leaving the checklist card sticking part way out of its holder, as did the pilot in the "flaps to go" example, was a relatively effective cue because it was conspicuous, strongly associated with the deferred task, and somewhat unusual.

However, even normally effective cues may fail, if an individual's attention is heavily occupied by demanding ongoing tasks. Leaving the checklist card out is rendered less effective when the pilots become busy with normally-scheduled, last moment preparations to take the runway. These demanding tasks reduce the likelihood that pilots will notice or fully process the cue associated with the deferred intention to extend the flaps. Because retrieving deferred intentions must compete with the cognitive demands of ongoing tasks, the probability of remembering to perform deferred tasks decreases with workload (Stone, Dismukes, and Remington, 2001). Further complications can arise because the goals of the ongoing tasks provide substantial activation to retrieve memories associated with those goals and do not support retrieval of the intention to perform a deferred intention. For example, on approaching the runway, the goal of taking off and associated tasks are in the foreground, rather than the goal to remember to set the flaps and complete the Taxi checklist.

Responding to interruptions is a special case of prospective memory. Interrupting a task implicitly creates a need to remember to resume the interrupted task later. However, interruptions are often so salient and abrupt that individuals may not have time to encode an intention to resume, or even think to do so, much less to create conspicuous cues to serve as reminders (Dismukes, 2007; Dodhia and Dismukes, 2008). With little or no encoding of the intention and without identifying or creating specific reminder cues, forgetting to resume interrupted tasks in a timely manner is common. However, individuals may still remember to return to the interrupted task if they happen to notice some cue in the environment previously linked with the interrupted task or if they pause to review the status of all tasks at the moment. This process is, unfortunately, haphazard, and cannot be counted on to be reliable. Checklists and monitoring are, of course, major safeguards against errors of omission; the effectiveness of these safeguards is discussed later in this chapter.

The vulnerability to error caused by interruptions is illustrated by the earlier ASRS example in which the crew was interrupted by a flight attendant's interphone call just as they were about to perform the Climb checklist and reset the altimeters. The pilots immediately turned attention to the call that raised issues important to the flight, but these issues further occupied their attention. The pilots probably did not think to encode an explicit intention to resume the interrupted tasks, nor did they create conspicuous reminder cues. (Quickly creating cues is often not practical in the cockpit.) Further, the pilots probably did not suspect they would be likely to forget to perform highly practiced tasks such as running the checklist and resetting the altimeters, and probably did not think that they would need reminding.

Habitual tasks and automatic processing

Broadly speaking, humans have two cognitive modes of processing information to perform tasks; one involves conscious control (called controlled processing in the scientific literature), the other involves automatic processes that operate largely outside of conscious control (Barshi and Healy, 1993; Norman and Shallice, 1986; Schneider, Dumais, and Shiffrin, 1984; Shiffrin and Schneider, 1977). The conscious mode is slow and effortful, and it basically requires performing one task at a time, in sequence. Learning a new task typically requires conscious processing, which is why learning to drive a car or fly an airplane at first seems overwhelming; the multiple demands of the task exceed cognitive capacity in this mode. Automated cognitive processes develop as one acquires skill; these processes are specific to each task, they operate rapidly and fluidly, and they require little effort and minimal attention, which is why, once we become proficient at driving or flying, we can perform those tasks while listening to the radio or talking to our copilot. Automatically performing a task reduces mental workload, allowing the individual to attend to other tasks.

Conscious control is required in four situations:

1. When the task is novel,
2. When the task is perceived to be critical, difficult, or dangerous,
3. When a habitual (automatic) response to a situation must be overridden to respond in an atypical way (e.g., not lowering the landing gear immediately after intercepting the ILS glideslope during approach), and
4. To choose among competing goals or activities (Norman and Shallice, 1986).

Human performance is usually a mixture of conscious and automatic processing. This is certainly true for cockpit tasks, though the mixture varies with the task. For example, to an experienced pilot, manual flying is largely automatic, but revising a flight plan in the FMC requires a considerable degree of conscious processing.

Habitual tasks that are consistently practiced in the same fashion and in the same sequence become largely automatic. Many habitual cockpit tasks involve a series of discrete steps, such as performing the items on a checklist. Furthermore, each task is itself a sequential step within a higher order task; for example, preflight procedural tasks are steps within the higher order task of preparing the aircraft for departure. As discussed in the Ideal chapter, practicing the large number of procedural steps required in each stage of flight in the consistent manner and sequence prescribed by the FOM helps pilots learn to execute procedures automatically, thus substantially decreasing their mental workload.

An essential aspect of automatic processing of a procedural task is that executing each step of the task automatically triggers retrieval of the next step from memory. For instance, the fuel quantity check in the flight preparation flow subconsciously serves as an internal trigger for the oil quantity check because these two actions are prescribed in this sequence by the written procedure and thus are consistently executed in this order. And because tasks are normally executed in a set sequence, performing one task automatically *triggers* the next task to come to mind, thus forming a chain of actions that requires little mental effort to recall and execute. External events also serve as triggers; appearance of the gate agent at the cockpit door just before pushback triggers the captain to remember to hand the gate agent the signed flight release form. Environmental *context* contributes to this triggering process; if the captain encountered the gate agent outside the cockpit he would be less likely to think of the release form.

Strictly speaking, individuals do not need to form explicit intentions for habitual tasks—the intention is implicit in the action schema for the task, and execution of each step of the habitual task normally occurs without deliberation. Habitual activities, because they become automatic, are largely under the subconscious control of trigger events and contextual cues, and this process is highly reliable when events occur in their normal sequence and in their normal context. But what happens when tasks are deferred or otherwise performed out of their normal sequence and context? Deferring a habitual task rearranges the normal sequence of tasks and removes critical triggers that have become subconsciously associated with specific actions and which normally serve to initiate those actions. The deferred task is detached from the preceding actions and events that normally trigger it, and, conversely, the deferred task can no longer trigger the task that normally follows it. In other words, the habitual chain breaks. Furthermore, performing tasks that normally follow the deferred task may create the misimpression that the deferred task has already been performed.

For example, normally the captain calls for the Taxi checklist, triggering the first officer to take out the checklist card and start running the checklist. The captain, for his part, relies on the transition from the ramp to the taxiway as the trigger to call for the Taxi checklist. But imagine that on some flight, the captain becomes busy negotiating a congested taxiway in foggy conditions with a long queue of traffic in front. He delays calling for the Taxi checklist until he feels comfortable that he can devote the attention necessary for its execution. The first officer may have subconsciously learned to rely on the external trigger of the captain's request to initiate the checklist. If the captain has taxied past his normal external trigger point before the congestion is resolved and so forgets to call for the deferred checklist, the normal trigger for the first officer is also removed, and she is at risk to also forget the deferred checklist.

Another consequence of rearranging the sequence of tasks is that the deferred task must be executed at a time when it competes with other tasks normally performed during this period. These other tasks are supported by their normal context and associated triggers, but the deferred task is not. Suppose that in the previous example, it was necessary to defer the Taxi checklist until the aircraft approached the runway threshold; the environmental context of the runway threshold is strongly associated with final preparations for departure, and reminds the crew to make those preparations. But the runway threshold is only weakly associated with the intention to perform the deferred Taxi checklist. What's more, because the Taxi checklist is normally completed prior to arrival at the runway threshold, the environmental context strongly supports the impression that the deferred Taxi checklist task has already been completed. When the Tower controller issues takeoff clearance, the crew is prompted to taxi onto the runway and complete the final items on the checklist (transponder and strobes on, scan panel for warning lights, etc). These final preparations are well supported through long association with the environmental context, external triggers, and internal triggers, but the deferred task is not supported unless the crew had the foresight to create a conspicuous cue, such as putting the deferred checklist in the throttle quadrant, or has established a habit of always asking themselves before taking the runway whether any items remain uncompleted.

This is exactly what happened to the crew in the ASRS example in which, after having to defer the flaps due to the icing conditions, the crew intended to set the flaps shortly before turning on to the departure runway (presumably when approaching the runway threshold). When the Tower controller gave permission for an immediate takeoff, the crew rushed to accept—crews typically try to assist air traffic controllers maintain the flow of aircraft; also, refusing the clearance would have delayed the flight. All activities associated with accepting the clearance and proceeding with the takeoff rose to the foreground, the environmental context and external cues supported proceeding with these activities, and the pilots did not review the status of the aircraft to determine if any deferred items were pending.

Problems can also arise in situations in which pilots must remember to substitute an atypical procedure in the place of a highly practiced procedure that has become habitual. In these situations, if the pilot does not monitor her actions carefully, she is vulnerable to reverting to the habitual action, a form of error called "habit capture" (Betsch, Haberstroh, Molter, and Glöckner, 2003; Reason, 1990, p. 68). For example, from long experience, a crew may come to expect a standard departure clearance at a particular airport that requires them to turn right to a heading of 300 degrees after reaching 1,000 feet of altitude. If on one occasion the departure clearance is modified to 330 degrees and the crew is busy during climb-out, they may revert to habit and stop the turn at 300 degrees. In this type of situation, as each step of the habitual sequence of actions is performed, it triggers automatic execution of the next step, and the atypical action is not substituted as intended. Here, too, creating explicit reminder cues that will be noticed during the turn can reduce vulnerability to this form of error.

Still another type of problem occurs when execution of habitual tasks is suspended, even briefly. In this situation memory of the many previous executions of the task may become confused with the current episode in which the task has not yet been completed, a problem called "source memory confusion" in the research literature (Johnson, Hashtroudi, and Lindsay, 1993). Consequently the pilot may have a vague feeling of having executed the suspended task and may not be prompted to check its actual status. Another possible manifestation of source memory confusion arises when a pilot remembers to resume a suspended task but returns to the wrong place in the task (Mycielska and Reason, 1982). For example, while performing a checklist, a pilot might be interrupted by a radio call that requires suspending the checklist in order to respond. After the interruption is over, the pilot might remember to resume the checklist but inadvertently resume one item later than the item he was about to call out when the interruption occurred —thus skipping an item on the checklist. Little research has been published on this form of prospective memory error, but, for example, the act of beginning to reach for a switch but not completing the act, might become confused in memory with having actually positioned the switch, especially since the pilot may have consistently executed that procedural step in thousands of preceding flights (See further discussion in Dismukes et al., 2007).

Pilots and other individuals may drastically underestimate their vulnerability to forgetting to perform habitual tasks that are interrupted or performed out of sequence because in their experience execution of habitual tasks seems simple and reliable, and requiring little mental effort. Consequently, individuals may not think to take precautions, such as creating conspicuous reminder cues, because such precautions are not necessary when habitual tasks are performed in the practiced fashion, context, and sequence.

Switching attention

Pilots do not normally have the luxury of deferring one task until another is completed; they must often interleave two or more tasks, which they accomplish by performing a few steps of one task, switching attention to the other task to perform a few steps, and back and forth in this fashion. When two tasks can be practiced together consistently and frequently, the steps of the two tasks become interrelated, and the two tasks merge into a single integrated task. For example, pilots first learning to fly instrument approaches struggle to keep up with multiple tasks: scanning and interpreting each of several instruments and making adjustments to pitch, power, and roll. With practice, the steps of the several tasks become linked, and the pilot switches attention among the tasks automatically and with much less effort—the separate tasks have become integrated into the superordinate task of controlling the aircraft by reference to instruments. Performance in these types of situation is normally quite reliable, in large part because cues occur that remind the individual when the time comes to switch attention from one task element to another. In particular, completion of one task element automatically triggers recall of the next task element from procedural memory.[7]

In many situations, however, pilots must interleave tasks that have not been practiced together consistently, if ever. For example, consider the situation of a first officer who discovers a numerical error on the load sheet and must re-program the FMC during taxi. Programming the FMC makes substantial demands on conscious processing, and so is ideally accomplished during preflight, when the first officer can devote full attention to it—which is the way prescribed by FOMs. When the FMC must be re-programmed during taxi, the first officer must shift attention back and forth between that activity and the normal duties accomplished during taxi, such as monitoring the progress of the taxi to help the captain catch any threats or errors. This interleaving requires looking down at the computer display to perform a few programming steps, looking up briefly to scan out the window, and then looking back down to find where programming had been left off, continuing with a few more programming steps, and then again looking up to scan.

This situation requires the pilot to self-interrupt each task periodically, which we have argued elsewhere to be a special case of prospective memory (Dismukes, 2007); it is problematic because of the lack of good cues to alert the pilot that it is time to switch attention from one task to the other. Because both tasks have novel aspects that are not extensively practiced together in a set fashion, performing elements of one task does not trigger retrieval from memory of the intention to switch attention periodically to the other task.

Attention-switching has been studied in great depth in the basic research literature (see Pashler, Johnston, and Ruthruff, 2001 for a review). It appears that

7 The way in which information is organized and stored in memory distinguishes between *declarative* and *procedural* knowledge (Eysenck, 1994). Declarative knowledge is that to which individuals have conscious access and can state directly in some form. In contrast, individuals do not have direct conscious access to procedural knowledge, which is demonstrated through action. Declarative knowledge, by its nature, is flexible, allowing general principles to be applied to diverse situations. Procedural knowledge is much more specific to situations; individuals develop a characteristic response pattern to specific situations to which they respond repeatedly—this is the basis of habit. Retrieval and execution of procedural knowledge is largely automatic, not requiring much conscious effort—indeed, effort is required to inhibit a strongly established habitual pattern of responding.

switching attention between tasks involves two components that require the brain's executive control systems. The first component controls shifting from the goal of performing the first task to the goal of performing the second task. The second component controls replacing the rules for performing the first task with the rules for performing the second task. Experimental studies using a paradigm in which participants either have to repeat the same task or alternate between two tasks within trials in a block have shown that alternating tasks imposes a switch cost—additional time is required after a switch to perform the next task (Rubinstein, Meyer, and Evans, 2001). Depending on the nature of the tasks, this cost ranges from a small fraction of a second to over one second. Such studies, however, do not adequately capture elements of real-world situations in which the pattern of switching required is not simple and constant, as it is in the laboratory. Still, we speculate that the switch cost may be related in some fashion to vulnerability to forgetting to switch in real-world situations.

Another component of attention-switching not fully captured by studies in the laboratory has to do with the issue of forgetting to switch tasks in a timely fashion—participants in the laboratory know when to alternate tasks between trials, and the time is so short between trials that prospective memory failures are rare. Complicating matters in real-world situations is that there is no established, agreed-upon schedule for how long it is acceptable to attend to one task before attention must be switched to the other task—this is situation-dependent, highly variable, and up to each pilot to work out for himself. This variability from one situation to the next contributes to errors. In situations that require interleaving tasks with novel aspects, pilots are vulnerable to becoming absorbed in one task and forgetting to switch attention to check the status of the other task and perform steps of that task if needed (Dismukes et al., 1998). This is especially true with tasks that demand a great deal of attention, as do programming and communication tasks. "Everything changes" is an example of successful task switching between re-programming the FMC and monitoring the taxi progress, whereas the ASRS report of violating the "hold short of taxiway E" clearance at LaGuardia earlier in this chapter illustrates failure to switch between a communication task (copying a clearance) and the task of monitoring taxi progress.

Little research exists to explain the cognitive processes that enable individuals in the situation of the pilots in "everything changes" to remember—at least some of the time—to periodically interrupt the ongoing task and check the status of other tasks. In some respects this situation resembles what is called *time-based* prospective memory (Brandimonte, Einstein, and McDaniel, 1996; Cicogna, Nigro, Occhionero, and Esposito, 2005). Most of the prospective memory situations described earlier in this chapter involve *event-based* prospective memory, in which the conditions under which an individual wishes to perform a deferred task are defined in terms of events (e.g., "We will set the flaps when we reach the hold-short line"). In contrast, in time-based prospective memory the conditions for performing the deferred task are defined in terms of time (e.g., "I will check the status of fuel transfer every two minutes").

The cognitive processes underlying time-based prospective memory may differ in important respects from those of event-based prospective memory, but these differences have not yet been studied extensively. Researchers have established that performance in time-based situations is considerably less reliable (Einstein and McDaniel, 1996), probably because the deferred intention is not associated with specific external cues that will prompt individuals to remember the intention at the right time. It is not known what does enable individuals to sometimes remember to perform time-based prospective memory tasks. In some situations individuals may set up a monitoring pattern in which they attempt to perform a few steps of an ongoing task and use the completion or outcome of those few steps to trigger remembering to switch attention to the other task. But the links between two tasks that have not been practiced together to any great extent is fragile; consequently this strategy is not always successful. Humans do have internal neural clocks, and it may be that such clocks help them keep track of the passage of time, but it is not known whether these clocks have any kind of alarm function. Here, too, the more demanding or engaging the ongoing task, the less likely it is that the individual will notice either internal or external cues signifying it is time to switch attention to the other task.

Switching among tasks is itself a task (if you will, a "meta-task") that makes further demands on limited cognitive resources. Furthermore, switching among tasks implies more than just the act of switching. Once the task switch has been accomplished, additional attention is required to acquire information and update situational awareness, a process that necessitates cognitive effort. This may explain why individuals report that having to switch among tasks increases the subjective experience of workload beyond that which would be expected from the simple sum of the demands of the two tasks (Kirmeyer, 1988a).

Having to concurrently accomplish several tasks that are not normally practiced together may also cause another kind of a problem, in that it often increases the total amount of work that must be accomplished in a set period of time. Crews have the authority to request additional time from a Ground controller who has issued a revised departure clearance, and sometimes they do, but the air traffic system provides considerable incentive to maintain the pace of operations and to avoid delays. Crews may be overly concerned with delays caused by losing a departure time slot or having to go around after falling behind in configuring the aircraft during approach. Subtle social factors may overly concern a first officer with not holding up a captain who is ready to proceed. These insidious pressures, which may be unconscious, push pilots to sometimes rush, which further increases vulnerability to error (Dismukes, et al., 2007).

Two crucial safeguards against errors of omission are checklists and monitoring (each pilot monitors the actions of the other pilot, the status of aircraft systems, and the path of the aircraft). But pilots are vulnerable to omitting checklist steps or entire checklists for the reasons discussed in the prospective memory section above. Monitoring is a concurrent task that often must be interleaved with other tasks. Thus, it is a kind of task-switching, vulnerable to errors of omission in the same ways as other task-switching situations. In the final chapter we discuss ways to improve the reliability of checklists and monitoring.

Applying These Cognitive Concepts to Cockpit Operations

With this cognitive foundation, we now analyze in depth four more examples from ASRS reports. These examples provide vivid and concrete illustrations of how crews respond to perturbations and the associated vulnerability to error. It will be apparent to the reader that these examples involve multiple operational issues, however, in each example we focus mainly on the cognitive processes that make any pilot in the reported situation vulnerable to error. Our analysis is necessarily speculative. The narrative of the ASRS report provides limited detail about what happened and what the pilots were thinking as events occurred. We flesh out the account with general knowledge of how airline operations are conducted, and we speculate on the cognitive demands from general knowledge of cognitive processes. Obviously, it is not possible to know exactly how cognitive processing actually took place in each of these specific incidents, but we feel that this approach provides a plausible account of the cognitive factors that would typically be at play in these situations. Thus, we are using these examples to expose our ideas about why concurrent task demands in routine flights are challenging and increase pilots' vulnerability to error.

Example 1: An interrupted procedure

Both reports presented below refer to the same incident that occurred to a crew flying the -200 variant of the B737 aircraft. The first report is the captain's account of events; the second is the first officer's account of the same events.

Report Number: 593973 (captain reporting):

> "... At the precise moment that I would normally call for the flaps to [be set to] their proper position for takeoff, the first officer, upon [pressing the annunciator panel, as required by the After Start checklist], reported [that] the low pressure light on the #1 electric hydraulic pump illuminated. We started looking for the hydraulic circuit breakers. The first officer pulled out the QRH [Quick Reference Handbook] and I called company to inform them of the problem and that we would be going back to the gate. The first officer eventually found a popped circuit breaker and it was successfully reset so I called company to inform them that the problem was corrected. This process took about 2–3 minutes… we pushed on time. We were not rushing and we were not fatigued nor were there any other mitigating factors [that caused our] failure to accomplish the proper checklist. Later, I asked why my first officer had stowed the checklist and he said he didn't normally do so but this time had difficulty with the circuit

breakers and needed both of his hands to accomplish the task of resetting the circuit breakers."

Report Number: 593896 (first officer reporting the same incident):

"…We checked [the] circuit breakers and did not [initially] see any circuit breakers popped. While the captain talked to Maintenance, I checked the QRH to look for [the] circuit breaker locations. I had to unstrap [my seatbelt] to look behind my seat at the bottom panel. I found one circuit breaker popped and informed the captain. He told me to reset [it]. The captain told Maintenance and they agreed we were good to go. This whole business took approximately 3 minutes. Normally, I leave the checklist [card] out after completing the After Start checklist. Today, in order to look for the circuit breaker, I put it back in its slot (before putting flaps to 5 degrees, and [before] performing the Before Takeoff checklist). After we solved our problem. I called for taxi [clearance]. We were rested, nobody was rushing, we were not talking about other things, we just did not do the Before Takeoff checklist ['Above the Line' items] (which we realized later). Taxiing to the runway, the captain asked for [the] 'Below the Line' [items]. I read [the checklist items], and he pushed the throttle forward—no takeoff [configuration] warning horn. Tower cleared us for takeoff. After advancing the throttles, the takeoff warning horn came on. We aborted the takeoff, checked the configuration, and realized that the flaps were up."

These two narratives describe a crew in the process of accomplishing the routine sequence of activities following a successful start of both engines. Per company procedures, while still on the ramp and before beginning to taxi, the first officer is supposed to accomplish the After Start checklist, the last item of which calls for a check of the annunciator panel, which the first officer accomplishes by pressing on the panel. If the system has detected an anomaly in any of the major aircraft systems, the corresponding light (and inscription) will illuminate on this panel to alert the crew. At the completion of this check (and of the checklist), the captain is supposed to call for flaps to be set to their takeoff position[8] and request that the first officer acquire the taxi clearance so as to release the brakes and begin taxiing. When taxi clearance is received, the crew must perform part of the Before Takeoff checklist (Above the Line items[9]) before the captain releases the brakes and sets the aircraft in motion.

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8 Flaps are set to their "takeoff position" when they are positioned appropriately for the particular takeoff. This is usually setting 1 or 5, but depends on the particular aircraft and performance issues (e.g., weight, runway conditions) so the crew calculates it on each flight prior to pushing back.

9 Standard Operating Procedures vary slightly among carriers (see "Ideal" chapter). Some airlines (like the one referred to here) specify two separate checklists (Before Taxi and Before Takeoff)—others specify one checklist (Before Takeoff) and distinguish between

Here we see that, upon pressing the annunciator panel, the first officer discovers it indicates a problem with the hydraulic system of the aircraft. This prompts him to look up above his head on the hydraulics panel to identify the source of the problem. This unforeseen interruption must be addressed immediately, so it requires the first officer's attention and disrupts the normal flow of activities (which is to confirm that no annunciations exist, call the checklist complete, and proceed). The first officer is forced to suspend the checklist, which can only be considered complete when all annunciations have been addressed. The first officer *implicitly* intends to resume the interrupted checklist after determining the source and possible solution for the hydraulic problem, but he may not encode an *explicit* intention to do so. He does not attempt to devise an explicit cue to help him remember to complete the checklist. The urgent nature of the interruption, as well as the sense of time pressure as the aircraft is about to start taxiing, does not encourage the first officer to identify or create a suitable cue. As is his usual practice, he continues to hold on to the checklist card from which he has just read the checklist items.

The first officer now turns his full attention to the task at hand—the interruption. He reports the problem to the captain and together they determine that one of the pumps appears to be indicating low pressure. Based on their experience with previous encounters with such an indication, the crew decides to first check the related circuit breaker.[10] An initial visual check of the circuit breakers does not reveal anything amiss. The captain contacts Maintenance over the radio and the first officer takes the opportunity to double-check the circuit breakers. This time he looks at the circuit breaker layout depicted in the Quick Reference Handbook (QRH) to identify the exact location of the relevant circuit breakers. Their location, behind his seat and near the floor, forces the first officer to unstrap his seatbelt. It may be at this point that, without thinking too much about potential repercussions, the first officer places the checklist card he has been holding back in its slot on the glareshield, directly below the front windows. This will allow him more freedom of movement and the chance to accomplish a more thorough visual check. Indeed, this time, the check reveals a popped circuit breaker. The first officer informs the captain who requests that the popped breaker be reset. Resetting the breaker involves pushing the tiny button back in and the first officer finds that he will need

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two portions (Above the Line and Below the Line items) to be completed before taxi and before takeoff correspondingly.

10 Quite often, the source of a problem is a "popped" circuit breaker. Like household circuit breakers, such devices in the aircraft interrupt electrical power to a protected system when they detect a malfunction. Many times, however, the circuit breakers have been pulled by the maintenance crew needing to make some adjustment/repair and are then inadvertently never reset. It is not uncommon for crews to fail to notice the position of a circuit breaker—there are over 100 tiny breakers to be checked on one panel. Specific rules dictate whether the crew is allowed to simply reset a popped circuit breaker and what precautions they may have to consider.

both hands to reset this particular breaker (if he has not already done so, he now places the checklist card back in its slot on the glareshield to free up both hands).

At this point, the first officer has not finished executing the After Start checklist. He normally keeps this card out because, immediately following the completion of the After Start checklist, he expects the captain to call for him to set the flaps, obtain taxi clearance, and perform the next checklist (Before Takeoff checklist). Having the card handy helps speed things up. Today, because of the situation with the popped circuit breaker, it is necessary to place the card in a secure location so that it does not fall or get misplaced, and that location is the slot where it is normally placed when not in use.

With the problem satisfactorily resolved, and having confirmed with the company dispatcher and with the maintenance crew that they will be proceeding with the flight as planned, the crew attempts to pick up their activities where they had left off. At this point, the tasks immediately pending on the captain's side are to call for flaps and taxi clearance. The tasks pending on the first officer's side are to ensure the After Start checklist has been accomplished and announce it "complete" and to respond to the captain's request for flaps and clearance. The captain asks the first officer to request the taxi clearance from the Ground controller, but in doing so, he inadvertently omits the normal call for setting the flaps for takeoff. The time spent dealing with the circuit breaker problem, contacting the company dispatcher, and contacting Maintenance has broken the normal sequence of closely linked actions, each action automatically triggering retrieval from memory of the next highly practiced step in the procedure. The situation now facing the crew is that after the delay they are ready to go (as far as they recognize), but they cannot proceed until they obtain taxi clearance. Thus the context of the situation provides better cueing for requesting taxi clearance than for calling for flaps.

The first officer, having just completed troubleshooting and resolving the unanticipated complication with the hydraulics, is also ready to get the flight going. Setting the flaps is so strongly associated with the cue of the captain's call for flaps to be set, that the first officer probably subconsciously depends upon this cue to prompt him, not just to act, but also to think about the need to set the flaps at this point. The captain's instruction to call for taxi clearance starts the first officer on the beginning of a habitual sequence of actions that normally occurs after flaps have been set. Thus, little occurs to prompt the first officer to think about setting the flaps, and starting the series of habitual actions that occurs after flaps are normally set may conceivably generate some sort of subconscious feeling that the flaps have been set—an example of source memory confusion. A deliberate search of the environment and memory for actions not completed at this point would probably have called both pilots' attention to the flaps. In the final chapter we discuss countermeasures, such as reviewing the status of items completed and uncompleted after a major interruption. It is especially important to conduct a review before moving on to the next phase of flight—in this case, starting to taxi.

To defend against inadvertent omissions, airlines use checklists of critical procedural steps. In this stage of the operation, standard operating procedures require the captain to call for the Before Takeoff checklist and for the first officer to execute these items before the brakes are released to begin taxi. One of the items on this checklist calls for the crew to confirm that the flaps have been set. As highly experienced pilots, the crew would have performed this checklist in its normal sequence on many previous flights. However, the circuit breaker interruption disrupted the flow of actions that normally prompt the crew to remember to perform this checklist, just as the interruption disrupted the flow leading to setting the flaps. Also, the first officer reports normally keeping the checklist card out after accomplishing the After Start checklist and until the Before Takeoff checklist; and very probably, through long association, the card serves as a helpful reminder to perform the Before Takeoff checklist. However, on this occasion the first officer put the card back in its holder, out of sight, in order to reset the circuit breaker, and this atypical action removed the cue that normally triggers the checklist.

The crew taxis to the runway and continues preparations for takeoff, both pilots unaware that they have forgotten to set the flaps and to run the Before Takeoff checklist that would have caught the omission. Although checklists provide a crucial defense against errors of omission, this incident reveals a subtle weakness in this defense. Situations that engender errors of omission, such as not setting flaps, can at the same time make the crew vulnerable to forgetting to perform the entire checklist that would catch the omitted procedural step.

This example illustrates features of the prototypical situation of “interruptions and distractions” discussed above. In this case, the interruption is an unanticipated new task—resolving the malfunction of the hydraulics system—which requires the crew to temporarily suspend preparing the cockpit for taxi. Suspending these preparations implicitly creates a prospective memory situation in which the crew must remember to resume preparations at the point at which they were suspended.

Example 2: A task cannot be executed in its normal sequence

Report #263589 (first officer reporting)

(The crew has just had the aircraft deiced twice and has resolved some problems with the Auxiliary Power Unit (APU) while still at the gate. Both engines have finally been started and the aircraft is ready for taxi):

> “... The captain elected to keep flaps up because of snow on the taxiways. Flaps are normally [extended] at this point which is part of the first officer’s flow. We did not complete the [Taxi] checklist at this point because we were holding the flaps up. As we sat in line for takeoff we discussed [reasons for the problem with the APU]. When we were next for takeoff, the captain instructed me to tell the Tower we needed 1 minute on the runway [to run engines up… per aircraft manual] and with parking brakes set for me to go back in the cabin to check the wings for [ice or snow] contamination. As we taxied into position on the runway, I completed the last items of the Takeoff checklist.. I had not

> noticed… that we had not completed the Taxi checklist… [which is] always done long before reaching the hold short line [of the runway]. During the wing contamination inspection I still did not notice the flaps were up... As the throttles were advanced... the takeoff warning horn sounded."

This crew has already spent more time at the gate than anticipated, due to a mechanical problem and the consequent necessity to repeat the deicing procedure, and is now finally ready to taxi to the departure runway. Both engines have been started. Normally, the captain would next call for flaps. After assessing the ambient conditions, however, he decides to defer the habitual action of setting flaps for takeoff. Depending on their experience with cold weather operations, both pilots have probably had to defer extending the flaps from time to time on previous flights.

Deferring the flaps, however, also requires deferring the Taxi checklist, since this checklist contains a step requiring that the crew verify the flaps are actually in the takeoff position. Appropriately, he intends to perform the checklist after setting the flaps—in this case, sometime before taking the departure runway. Both pilots undoubtedly intend to set the flaps and perform the Taxi checklist later, right before takeoff.

Setting the flaps is a strongly habitual action of such critical importance for safe takeoff that the crew may not suspect they are vulnerable to forgetting to perform it. Performing the checklist is also a highly practiced activity that is probably not considered a candidate for inadvertent omission. Because experienced airline pilots have accomplished these actions thousands of times previously, and because remembering to perform them pops into mind automatically and effortlessly when procedures are performed in the normal sequence, the crew is not aware of any compelling reason to take special efforts to guard against a possible omission on this occasion.[11]

Following the decision to defer flaps, everything else proceeds normally, and the crew devotes attention to taxiing under the demanding conditions posed by snow on the taxiways. They also report engaging in a discussion about the APU. Although the problem they had encountered earlier was resolved before pushback, it is normal for pilots to continue discussing the reasons behind the malfunction and how it might later affect the flight. However, conversation makes considerable demands on attention, and this discussion may make the crew less likely to review the state of preparedness of the aircraft before takeoff.

When the Tower controller issues a clearance for takeoff, the captain recognizes that the aircraft has spent more time idle than he may have anticipated. With appropriate caution (and following standard procedure) he asks for a visual inspection of the wings for snow or ice. This check is performed by the first officer who physically goes back to the cabin and views the wing surfaces from the side windows. (The crew asks the Tower controller for a slight delay, which is not uncommon in this situation.) The first officer visually determines that the wings

11 The crew reporting this incident did not mention having created a cue to help remind them of the deferred task, so we assume that they did not.

are clean. Intent on checking for ice or snow, however, he does not notice that the flaps are not extended. Though failing to notice may seem surprising, it is in fact a common phenomenon in which the way people frame a task strongly influences what aspects of a situation they notice and what aspects they do not notice (framing: Tversky and Kahneman, 1981; Loft, Humphreys, and Neal, 2004).

When the crew receives clearance for takeoff, the captain advances the throttles. All external cues as well as the environmental context are consistent with the normally-encountered Pretakeoff phase during which the flaps have been set and Taxi checklist has been completed, and the only thing pending is the completion of the Takeoff procedure and checklist. In some sense, this situation closely resembles that of the previous example. The forced deferral of setting flaps has broken the normal chain of events and actions that trigger retrieval from memory of taxi related actions (i.e., extending the flaps and performing the Taxi checklist). Those triggers belong to the past—and were "ignored" after the conscious decision to defer both setting the flaps and conducting the checklist. Now, with the aircraft close to the runway threshold, in the place of these triggers are other cues normally associated with initiating the takeoff; the crew's mental frame of reference is therefore oriented to taking the runway, and it's attention is occupied with the last minute tasks necessary for takeoff. Unaware that the flaps are still up, the captain advances the throttles. Fortunately, the takeoff warning horn prevents the impending disaster.

This example illustrates features of the prototypical situation of "tasks that cannot be executed in their normal, practiced sequence." Allowing for certain activities to be executed automatically, based on practice, habit, and the development of subconscious triggering events and cues, is an important feature of aviation operations. Were it not for the largely automatic execution of highly practiced procedures it would not be possible for pilots to accomplish all the tasks that must be performed to fly an airliner. But this incident illustrates that the cognitive processes underlying expert execution of practiced skills—highly reliable when procedures are executed in their normal sequence—are vulnerable when the normal sequence is disrupted. In this case, the task normally and automatically executed prior to taxiing (setting the flaps) cannot be executed and is deferred for later—the normally associated triggers are thus lost. Not specifying exactly when it will later be accomplished, or what the new trigger will be, the automatic action of setting the flaps and executing a checklist is later never triggered. In the final chapter we discuss ways pilots can use more deliberate, conscious cognitive processing to keep track of automatic execution of procedures, and other countermeasures to reduce vulnerability to error.

Example 3: A new task must be deferred

Report #443000 (flying pilot reporting):

> "... We were about to begin our descent… when a flight attendant knocked on the cockpit door… Upon entering the cockpit the flight attendant asked the captain and me about [non-essential conversation]... During the conversation, which

> we all 3 [captain, first officer, and flight attendant] participated in, the Center controller told us to cross 35 miles E[ast] of KNOX at FL250 [25,000 ft]. This was read back to him and a quick calculation showed that we had about 25 miles to go before needing to start down. The conversation with the flight attendant continued and then concluded… I then proceeded to brief the approach… and totally forgot about the assigned crossing restriction."

In this example, the crew is interrupted by the flight attendant while in the cruise portion of the flight, when their workload is quite low—their main duties are monitoring the autopilot follow the pre-programmed flight plan and monitoring the radio for potential instructions from the controller. Both pilots become involved in the ensuing conversation, which is not uncommon during a phase of flight that places low demands on pilots' direct attention. The pilots probably assume the conversation will not prevent them from concurrently keeping an eye on the autopilot and monitoring the radio.

In these sorts of situations, casual conversation is a double-edged sword. Because humans are inherently quite poor at maintaining vigilance and alertness for long periods with minimal mental stimulation, conversation helps crews maintain alertness. But even a casual conversation makes substantial demands on attention, and it is easy to become engrossed in conversation and inadvertently let monitoring drop away (Dismukes et al., 1998). In this instance, the casual conversation does not, however, seem to distract the crew too much, and the two pilots monitor well enough to notice and acknowledge the controller's radio message assigning a crossing restriction.[12]

This example illustrates features of the third prototypical situation of an "additional, unanticipated task demand" discussed above. The controller's instruction is the new task demand added to the normal sequence of requirements and activities of this phase of flight. A quick calculation reveals they are about 25 miles from the point at which they must start their descent in order to comply with the crossing restriction; it will take three or four minutes at typical speeds to reach this point, and the crew returns to the conversation with the flight attendant. The additional task demand therefore also carries a prospective memory element to it, as the crew needs to create a deferred intention to start on a descent at a specific point that will allow them to reach the assigned point (35 miles east of KNOX—a navigational fix point depicted on their charts) at the instructed altitude.

The pilots were very probably unaware of the cognitive vulnerabilities to which they were exposed in this situation. Because crossing restrictions are commonly a part of descent clearances, and because the content of the restriction is simple and familiar in form, the pilots probably did not suspect they were vulnerable to

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12 The sparse narrative of the ASRS report does not provide detail, but we infer that the crossing restriction required them to descend before they would have normally had to in order to get down to the airport.

forgetting to execute the intention and did not make any special attempt to encode the intention and create a specific cue for it. The conversation may have further limited the extent to which the pilots encoded the crossing restriction in memory, and it probably prevented them from rehearsing the intention to help keep it active in working memory. Thus, the intention to descend early to make the crossing restriction had to be retrieved from long-term memory when the aircraft reached the descent point.[13] The pilots had to observe the Navigation Display[14] to monitor their position. We do not know how frequently the pilots monitored the Display while continuing the conversation, but they did pay enough attention to their situation to recognize when they were at the point they would normally begin their preparations for descent, and at this time the flying pilot began his descent briefing.

Why did both pilots fail to retrieve from memory their intention to descend early at a specified point to meet the crossing restriction? Their cue to descend was provided by the Navigation Display, however this cue by itself was an imperfect trigger for retrieval from memory, even if they looked at it at the moment the aircraft reached the descent point. The display has many associations in memory (the "fan" effect) and has at best a fair chance of triggering retrieval of the intention to descend early unless the pilots establish a procedure of periodically monitoring the display and determining each time they check it if they are yet at the descent point. In principle, the pilots could interleave monitoring the display this way with their conversation, yet, as discussed in the next example of a prototypical situation, interleaving has its own vulnerabilities.

Example 4: Interleaving new tasks with ongoing tasks

Report #259087 (first officer reporting):

> "As the aircraft approached the airport we received [navigation instructions from the controller] for runway 17R. The reported weather changed several times [during final approach]. Air Traffic Control asked if we wished to land on runway 18L. [Based on reported visibility conditions] we elected to accept runway 18L. The aircraft was configured on schedule to flaps 30 degrees as briefed. I began to re-program the computer for runway 18L [in order to obtain improved situational awareness]. This task was complicated by an inoperative 'execute' button [on the FMC]. The captain requested flaps 40 degrees and briefed a new

13 This is typical of situations in which pilots form intentions to perform an action at a later time. Although in this incident the pilots could have put aside non-essential conversation and rehearsed the intention, it is not common for people to maintain intentions in working memory by continuous rehearsal except for very short periods of time such as between looking up a phone number in a phone book and actually dialing the number.

14 In older aircraft that lack Navigation Displays the pilots must monitor position with a Horizontal Situation Indicator and Distance Measuring Equipment. We do not know what type of equipment this aircraft had.

> approach speed. I selected flaps 40 degrees and continued re-programming the computer. The runway approach lights could be seen illuminating a thin layer of fog. We were still [flying in] VMC [visual meteorological conditions]. I heard the ground proximity warning [horn] sound. I scanned the instruments and saw the captain begin raising the nose and advancing the thrust levers [to abandon this attempted approach and landing]… I reported the Missed Approach [to the Tower controller]."

Weather conditions precipitate a change in the arrival/landing plans for this aircraft during approach. This is not uncommon, and the crew prepares to handle the additional tasks incurred by accepting a runway change. The first officer decides to re-program the FMC, which will provide additional flight path information to support situation awareness. Re-programming the FMC must be interleaved with the normal duties of the monitoring pilot (the first officer): monitoring the status of the aircraft, executing commands given by the flying pilot, and performing checklists. To accomplish all these tasks, the first officer has to restrict performing each task to a few seconds at a time, and must attempt to remember to switch attention back and forth among the several tasks.

We have already discussed the reasons pilots are vulnerable to becoming absorbed in one task and forgetting to switch attention to other tasks with sufficient frequency when interleaving. This is especially a problem when the ongoing task demands full attention, as does re-programming the FMC. In this incident, an additional complication arose because the Execute button on the FMC was inoperative, and this complication undoubtedly increased attention demands (and time pressure) still further. Perhaps the first officer anticipated being able to re-program the FMC so quickly that he would not be head-down very long, not recognizing that any unexpected complication may cause him to lose track of other interleaved tasks.

This example illustrates how unanticipated new task demands may force pilots to attempt to interleave several tasks concurrently (the third and fourth prototypical situations). In this sort of situation, with the first officer head-down and mentally absorbed in the FMC task, little existed to prompt the first officer to remember to frequently suspend the FMC task and look up to monitor the aircraft situation. The captain's call for flaps 40 briefly pulled the first officer's attention away from the FMC task, but the first officer then returned to that task which now preoccupied him because it took longer than anticipated due to the Execute button problem. The first officer was slow to look up again until the ground proximity warning aural alert interrupted his preoccupation. Apparently the captain had let the aircraft descend too low or had allowed an excessive rate of descent, triggering the warning. Incidents such as this have occurred with such frequency that some airlines now advise pilots to consider not re-programming the FMC when runway changes are given close to the airport. Instead, the monitoring pilot can back up the flying pilot with data from the cockpit instruments more quickly and with less prolonged diversion of attention.

Conclusion

In this chapter, we have provided what we think is a plausible account of the reasons the demands of managing concurrent tasks in real world flight operations increase pilots' vulnerability to errors of omission. This account is of necessity somewhat speculative because much more empirical research is needed, but it is consistent with existing scientific knowledge. The ideal of how flight operations should be conducted, as manifested in FOMs and associated training is frequently perturbed in diverse ways, but most perturbations resemble one or more of four prototypical situations:

1. Interruptions and distractions;
2. Tasks that cannot be executed in their normal, practiced sequence;
3. Unanticipated new task demands arise; and
4. Multiple tasks that must be performed concurrently.

Each of these situations creates task demands that must be managed, if not performed, concurrently. Of necessity, pilots respond to these prototypical situations either by deferring tasks or attempting to interleave tasks. With both types of response, pilots—and any other individuals dealing with concurrent task demands—may forget to perform intended tasks in a timely manner. In the final chapter we explore the implications of our analysis and suggest countermeasures that might reduce vulnerability to errors of omission.