Chapter 6

The Research Applied

In the Ideal Chapter we showed that operating procedures for normal flight situations are designed as if flight operations are linear, predictable, and under the complete control of the crew. Moreover, we argued that the training that is based on such procedures, and which to a large extent is designed to teach and practice these procedures, further conveys this implicit perspective about the nature of flight operations. However, as we showed in the Real Chapter, this perspective is inconsistent with the reality of day-to-day airline operations. The Analysis Chapter explained some of the risks resulting from the interaction between the nature of human cognition and these discrepancies between the ideal and the real. In the present chapter, we discuss specific implications and applications of our work for the design of procedures and training. We also describe how one major carrier applied our analysis, and we conclude with a more general discussion of ways in which individuals and organizations can reduce risks and improve human operators' ability to manage the complex demands of real-world operations in all types of dynamic work environments.

Airline pilots undergoing training are required to learn by rote the exact steps and actions within procedures, as well as whole sequences of procedures, and then practice them repeatedly, always in the same manner, until whole procedures are committed to memory and can be performed in an almost automatic fashion. (This is also true of the training of operators in many other complex systems involving formal procedures.) Steady improvement in accuracy and fluid execution of procedures is often used to indicate progress during training. Performance is regularly assessed in tests that require pilots to operate a flight simulator and perform many normal and non-normal procedures to demonstrate their mastery of these procedures. Because of regulatory requirements, as well as time and cost constraints, these tests are focused primarily on the pilot's control of aircraft and operation of its systems, including procedures to configure those systems for flight and for rectifying problems that may arise with those systems. Training and testing do not fully capture how these procedures are used in actual line operations; in particular, the complexity of actual operations and the necessity of managing multiple tasks concurrently are drastically under-represented. In other words, these tests and the training that prepares a pilot to pass them are often conducted as if the pilot is the only pilot in the sky, and the aircraft the only aircraft in the sky.[1]

1 It is interesting to note that this same attitude often underlies aircraft design as well. Thus, FMC logic is designed to optimize performance of the particular individual aircraft as if no other aircraft share the same airspace. As a result, optimal flight paths dictated by

Thus, the training and the testing reinforce the ideal perspective and exacerbate the discrepancy between the ideal and the real.

As the many examples from our observations, from ASRS reports, and our analyses of these events show, anytime the assumptions of linearity, predictability, and controllability of operations are violated, the risk of erring increases. What's more, procedures and training that are based on these ideal assumptions unintentionally set traps into which pilots sometimes fall. The risk of erring further increases with increasing demands of concurrent task management, as when crews are in any of the prototypical situations we examined earlier. In the next section, we describe how the analyses we have presented in the preceding chapters led one major airline to review and revise its operating procedures to remove these traps and reduce these risks.

Reviewing and Revising Procedures

At the completion of our observational study, we delivered our findings to the airlines that had granted us access to their cockpits. One of these airlines decided to revise its procedures, in part because it became particularly concerned that its operations could be vulnerable to the operational perturbations we reported having observed during its daily flights. The airline decided to revise its normal procedures by questioning everything in its then-current normal procedures, and enlisted our assistance with the review and revision process. A team was assembled, and tasked with reviewing the airline FOM and with proposing changes to improve safety and efficiency. We provide here some details about the team's composition and the process they followed (for further details, as well as in-depth discussion of reviewing and revising operating procedures, see Barshi, Mauro, and Loukopoulos, in preparation). We then use one example to illustrate the outcome of the team's effort, focusing on the types of issues treated in this book. We believe that the work of this team could serve as a model for any organization (i.e., not just an air carrier) wishing to reduce the kinds of risks our analyses expose.

As should be clear from the discussions throughout this book, designing good procedures is neither trivial, nor obvious. Simply understanding the relevant equipment and how it is to be used is not enough. Operating equipment safely and efficiently also requires a thorough understanding of the operator, of the environment in which the operations take place, and of the operations themselves. It is crucial, therefore, that all these different perspectives be taken into account in the design process for the resulting procedures to be optimal.

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the FMC often have to be interrupted in response to ATC instructions which attempt to accommodate other traffic. These path interruptions often have adverse effects on safety in addition to their impact on efficiency.

Following this principle, the airline staffed its review team with active line pilots of varying levels of experience and seniority, including check pilots,[2] senior and junior captains as well as experienced and junior first officers. The team also included representatives of the Training Center, the Safety Department, and the Pilots' Union. When needed, the team also called on the expertise of regulatory bodies, the Engineering Department (both at the airline and at the airframe manufacturer), Scheduling and Dispatch departments, and even Customer Service for issues that had implications for their passengers. In arranging this broad representation, the airline assured adequate input throughout the review process from all stakeholders, as well as commitment to the process and buy-in for the final product.

The team started its work with a thorough analysis of the existing procedures and developed an extensive catalogue of hidden *traps*, that is, instances that resemble the prototypical situations described in the previous chapter and that hold the potential for errors. In particular, using their own expertise as pilots and additional jumpseat observations of their own, team members looked for conflicts, such as those that arise from the opposing demands sometimes placed by procedural requirements and those placed by the nature of the operation (i.e., by operational perturbations), or those between procedural demands and cognitive capabilities.[3] An example of the first (conflicts between procedural and operational demands) would be a Taxi checklist that has to be executed during taxi, or a procedure to be performed at a time when the crew is likely to receive a radio call from ATC. Performing a checklist during taxi creates a conflict because the crew must focus on a number of operational tasks, such as the control and movement of the aircraft, the continuous awareness of the layout of the airport's taxiways, the proper execution of the taxi clearance received from ATC, the location and movement of other aircraft and vehicles, and the communication exchanges on the radio to maintain situation awareness€. Requiring the crew to divert their attention from all these tasks in order to focus on executing a checklist at the same time is one of the reasons for the large number of surface incidents and runway incursions that occur annually (FAA, 2007). Similarly, there are known altitudes and locations where there is a high likelihood of receiving radio calls from ATC. These are the altitudes and locations where "hand-offs" take place, such as when the departure controller hands a flight off to the low-altitude center controller, or where one enroute center

2 Check pilots (or check airmen) are experienced line captains especially trained and designated by the FAA to conduct advanced training and all testing and certification of pilots at their airline. They also act as quality assurance officers, maintaining the standards according to the airline's FAA-approved certificate of operations.

3 The review team searched for and identified other types of conflicts such as between procedural demands and current equipment or between procedural demands and current company philosophy. Here we focus on those elements of the team's work most closely related to the theme of this book. For a more comprehensive discussion of this team's work and of such a process in general, see Barshi et al., (in preparation).

controller hands off a flight to another center controller. These hand-offs require two separate communication exchanges, one with each controller, and a radio frequency change in between. Requiring the crew to perform a procedure during such a time sets a trap that increases risk, because completing the procedure will have to be deferred until the communication exchange with ATC is finished.[4]

The review team first combed through their existing procedures, examining them through the lens of the reality of everyday operations to identify conditions that could lead to any of the prototypical situations we described earlier. Next, the team explored alternative means of completing the same tasks as a way to alleviate the potentially risk-inducing conditions. Proposed changes were extensively tested and evaluated in flight simulators, leading to an iterative process of refinement. The final product was implemented and shown to result in substantial reduction in error rates and in improved efficiency of flight operations. Many of the traps were successfully removed, thereby minimizing the opportunity for any of the prototypical situations to occur. The revised procedures were also shown to be easier to learn than the old procedures, thus enhancing the airline's training program. To illustrate some of that process, we turn to one detailed example. We look at the analysis conducted on that particular problem area by the review team, at the procedures before and after the revision process, and at the way in which these procedural changes alleviate the risk-inducing conditions and increase the safety of operations.

Setting flaps for takeoff

To complement its analysis of procedures and operational perturbations, the review team used pilot reports collected through the airline's own safety reporting system to identify challenging areas in the airline's operations that threatened to give rise to serious incidents or even accidents. One significant problem area identified was the situation in which crews inadvertently omit setting the flaps prior to takeoff, a situation already referred to in other ASRS examples in this book. The attempted no-flaps takeoff error is serious because it can have fatal consequences. Large transport category aircraft are not designed to take off with flaps[5] retracted. To prevent this serious omission, the takeoff configuration warning horn provides an aural warning when the throttles are advanced on the ground and flaps are not set for takeoff. When pilots fail to execute the prescribed procedure and omit

4 Responding to ATC instructions must be accomplished as soon as possible, so it typically takes precedence over any other ongoing tasks.

5 All references to "flaps" in this discussion include both leading edge and trailing edge devices. In most aircraft, and certainly in the Boeing 737 which is used throughout this book, leading edge lift devices (such as slats) and trailing edge devices (flaps) are activated together by a single control.

setting the flaps, their lives hang by the single thread of the warning system[6]; they are only one fault away from catastrophe. Cases in which the crew inadvertently omitted the flaps and the warning horn malfunctioned have ended in fatal crashes (e.g., NTSB 1969, 1988, 1989). More importantly, the team also noted that when crews report having omitted setting the flaps, this omission was often only the most noticeable error because flap position is wired to the warning horn and is thus linked to a visible/audible outcome. In many cases, forgetting to set the flaps for takeoff, in fact, also involves the omission of the whole procedure and corresponding checklist in which setting the flaps is to be performed.

The original pretakeoff procedure

The original FOM described the After Start procedure, which was followed by a short After Start checklist, "silently" performed from memory by the first officer who also announced it "complete." The FOM then went on to discuss taxi considerations, following which it described the Pretakeoff procedure. The first item was "Wing flaps" for which the FOM stated:

> "The Captain will call for the flaps to be set. The First Officer repeats the command and places the flap handle to the takeoff flap setting and verifies that the handle position and flap gauge agree."

The procedure then continued with two additional items (controls check and performance computations) and a portion of the Pretakeoff checklist (Above the Line), followed by 8 more items and a second portion of the Pretakeoff checklist (Below the Line).

The original Pretakeoff checklist contained 24 items. The eighteen items listed as Above the Line were to be performed during taxi, whereas the 6 items listed as Below the Line were to be performed once the flight was cleared to cross the hold-short line (that is, either cleared for takeoff, or cleared into position on the departure runway). In the Above the Line subset of the Pretakeoff checklist, "Wing flaps" was the 10th item, just about in the middle of the list.

A section discussing "Weather Procedures" under Supplemental Procedures of the original FOM provided the following guidance: "If taxiing through slush or standing water in low temperatures, leave the flaps up. Taxiing with the flaps extended subjects them to snow and slush blowup from the main landing gear wheels. Leading edge devices are also susceptible to these slush accumulations."

Evaluating the operational context and cognitive demands Taking our findings into account, and discussing with us how these findings may apply to their

6 Such situations of a potential single-point failure were also a specific focus of attention for the review team. The intention was to provide multiple layers of defense and minimize the number of cases where a critical item is protected by just a single layer.

operations, the review team came to understand that failing to set flaps and similar errors of omission are linked to basic human cognitive vulnerabilities. Recall that the operational demands for concurrent task management often give rise to one or more of the four prototypical situations and expose the fragility of prospective memory, the downside of automatic processing, and the difficulty with switching attention between tasks. To understand how each of the prototypical situations (or their combination) may give rise to the omissions involved in the attempted no-flaps takeoffs, the review team considered the broader operational context within which flaps are supposed to be set. Their analysis revealed that the original procedures unintentionally created several traps that increased vulnerability to error.

Flaps must be set prior to takeoff. They can only be activated once sufficient hydraulic pressure is available, after the engines have been started. But besides these two boundaries at the extremes (engine start and takeoff), there are no particular requirements or specific conditions for the timing of setting the flaps for takeoff. Also, setting the flaps does not interact with other required actions or procedural steps in the Pretakeoff phase of flight (their activation does not depend on the execution of other items except for starting the engines and engaging the hydraulic pressure pumps; likewise, the execution of other typical pretakeoff items does not depend on the setting of the flaps). As a result, the captain's call for the first officer to set flaps for takeoff in many airlines' procedures has been what we have come to call a "floating item." *Floating items* are actions that are not specifically pinned down in time according to a specific procedure, though they may have to be accomplished within a given time frame (e.g., calling for the flaps must take place at some point after engine start and prior to takeoff, but can happen anywhere within this time frame).[7] By definition, because they are not pinned down in time, performing floating procedural items is inherently a prospective memory task, and as such is vulnerable to forgetting. In analyzing the interaction between the operational context and the operator from this perspective, the review team recognized that allowing a critical action such as the call for the flaps to float sets a trap for the crew.

The ground phase of operation prior to takeoff can sometimes be a very busy time of the flight, as the many examples given in the preceding chapters clearly show, and as LOSA data confirm. One LOSA study, for example, claims that 75 percent of safety-threatening factors occur during the Pretakeoff phase (Helmreich, Klinect, and Merritt, 2004), although the consequences of these factors may not occur until after takeoff. Risks associated with surface incidents and runway incursions have received much attention in recent years (Lacagnina, 2007; US GAO, 2007). Navigating the airport's taxiways can be very challenging

7 Note that this call is different than the "flaps" item on the taxi checklist which directs the crew to verify that flaps have been set earlier. The checklist is often performed during taxi and definitely before takeoff, implying that the crew has called for flaps to be set sometime before calling for the checklist.

even under the most benign conditions. Pilots must pay close attention to a large number of variables in a highly dynamic situation. Aircraft are large and taxiways may be narrow; taxi clearances can be complex and signage may be confusing; many airplanes and vehicles operate in close proximity and the distances are hard to judge. There are organizational pressures of schedule and fuel efficiency. The crew may even be distracted by personal matters, preoccupied with issues they bring with them to the cockpit from conversations in the pilot lounge or at home, or stressed from the drive to the airport or from the layover at the hotel . In the midst of it all, the crew must remain alert and prepared to respond to any number of variables that can change from one moment to the next (instructions to stop/move, change in taxi routing, departure information, or aircraft sequencing, etc). The challenges are substantially greater in conditions of reduced visibility, stormy weather, or heavy traffic—conditions that often mean delays and place further pressures on flight crews. In short, operating aircraft on the ground is often extremely demanding.

In this highly dynamic environment with its many demands, the captain must remember to call for the flaps to be set, while also being responsible for and directly engaged in controlling the moving aircraft. Because the call for flaps is a floating item, the captain must rely on fragile prospective memory processes to remember to make that call. Without being able to explicitly articulate the risky nature of this complex situation, many captains are intuitively aware of the floating nature of this call and of the fragility of their own memory, and so define for themselves a particular external cue to rely on. Some captains call for the flaps as soon as they receive their taxi clearance. Some when they begin their taxi. And some use the straight taxiway parallel to the departure runway as the reminder, because it represents a period of reduced workload.

The review team collected and documented personal stories throughout the airline and evaluated the kinds of cues pilots were routinely using to make sure they don’t forget to make the flaps call. The team found that such cues usually worked well, but not always. Because of the intensely dynamic nature of ground operations, cues can be easily obscured or rendered inapplicable. A captain relying on the beginning of taxi as the cue to call for the flaps can be interrupted by a radio call, or distracted by a provisioning truck maneuvering in close proximity to the airplane. Procedures that call for taxiing with flaps retracted in icy or slushy conditions render that same cue irrelevant since the flaps cannot be set at the beginning of taxi. A revised taxi or departure clearance introduces an unanticipated new task that may divert a captain’s attention from his normal cue, and executing checklists while taxiing requires concurrent task management by definition, another situation that may hide a well-intended cue. In analyzing the operating environment faced by their pilots on a routine basis, the review team realized that pilots were at risk of forgetting to make the call to set the flaps for takeoff because the conditions under which the flaps are supposed to be set provide many opportunities for one or more of the four prototypical situations to occur.

The review team also focused on the effective strength of the cues pilots were using for flaps. The more strongly the cue is associated with the intended action, the greater the chance of the task being recalled. External cues (in the environment) are usually more effective than internal ones (in the person's head), because they are more predictable than the stream of consciousness. Consider the difference between setting the flaps for takeoff and setting the flaps for landing. Flaps are crucial for both maneuvers, and in both cases the task of setting the flaps is a floating item and hence a prospective memory task. Namely, the pilot must remember to call for the flaps to be set for the intended maneuver. But it is extremely rare that pilots omit setting the flaps for landing, whereas setting the flaps for takeoff is highly vulnerable, as the various ASRS reports and the airline's own experience clearly show. The difference between the two maneuvers is in the number, strength, and reliable presence of external cues available to the pilot. Prior to landing, the pilot must descend and must slow the aircraft down from descent speed to approach speed. Even at idle thrust, the aircraft will pick up speed during descent unless additional drag is used. Speedbrakes and idle thrust are used to reduce speed, but flaps must be used to properly manage the descent path, pitch attitude, and speed. Not only are there clear external cues to remind the pilot to extend the flaps prior to landing, there is also clear feedback from the aircraft behavior once it is done. Control pressures, pitch attitude, speed, and descent path, all respond to the flaps extension. If the pilot were to forget to extend the flaps, it would be impossible to maintain aircraft control under the correct descent conditions of pitch attitude, speed, engine power, and descent path. In contrast, on the ground, there are no obvious external cues to remind the pilot to extend the flaps, and no change in aircraft behavior reflecting flaps extension. The aircraft feels the same way and taxis the same way regardless of the flaps' position. On the ground, prior to takeoff, the cues must be devised by the pilot, or better yet, designed into the procedures.

We must note here that some may argue that the real problem is one of workload. The demands described above might be simply treated by pilots as increased workload, and errors could be considered to be the result of this workload exceeding a given threshold of the number of tasks a person can perform at once. Such a view is based on the assumption that people can multitask reliably, that is, they can perform several tasks at the same time with no impairments to their performance of any one of the tasks. As we have already seen, however, simultaneous performance pertains only to tasks that have become automated and do not require appreciable attentional resources, and even then performance is not perfect. Non-automated tasks require controlled processing that can only be focused on one task at any given moment. Thus, even when it is possible to accomplish all tasks within the time available, performing more than one non-automated tasks at the same time means concurrent task management, in other words switching of attention back and forth among the tasks at hand with all the implications we have seen that has for performance. Thus, although high workload may exacerbate concurrent task demands, there is much more to the prototypical situations than the mere increase in the number of tasks that must be handled.

Interruptions and distractions were the common theme of the first prototypical situation described in Chapter 5 (Analysis). The time on the ground prior to takeoff is often busy and replete with interruptions and distractions. Taxi is a time when ATC may interrupt the crew with complex taxi instructions or amendments to the departure or enroute clearance, necessitating changing the FMC programming, or reviewing charts. We can safely assume that the longer a checklist, the longer it takes to execute it, and thus the more likely it is that some external event might interrupt its execution. The review team readily recognized that presenting a very long checklist (18 items Above the Line) at an interruption-prone phase of flight creates a conflict between procedural and operational demands, and substantially increases the crew's vulnerability to inadvertent omissions of checklist items.

Tasks that cannot be executed in the normal, practiced sequence of procedures were the common theme defining the second prototypical situation. Not only does the procedure calling for deferring the extension of flaps until the end of taxi when taxiing through slush or ice force the pilots to deviate from the normal practiced sequence, it also requires them to interleave an unanticipated task later in the sequence, the third prototypical situation. This procedure creates a prospective memory task, but does nothing to support encoding into memory the intention to extend flaps later or retrieval of that intention when the right time comes, at the end of taxi. The crew is, therefore, on its own with no procedural support, at a time when the flight is likely to be under many pressures. The weather conditions necessitating this procedure often create delays and congestion (both on taxiways and on radio frequencies), which lead to higher workload and time pressures. The review team recognized that there are no strong external cues to extend flaps and complete the Above The Line checklist at the end of the taxi, but in contrast there are plenty of cues (e.g., the sight of the runway, clearance to hold short of the runway or to takeoff) to prompt the crew to perform the Below the Line items. The crew is also vulnerable to implicitly assuming, based on habit built on the way things are normally done, that the Above the Line items must have already been performed if the aircraft is about to take the runway. These factors, plus the intrinsic pressure on the crew to depart without delay and not risk losing their place in the departure queue, create a high risk of omitting the flaps and probably the whole Above the Line checklist under these conditions.

Multiple tasks that must be performed concurrently were the defining characteristic of the last prototypical situation. A checklist that is performed during taxi is clearly such a case. Because airplanes can only maneuver on two axes rather than the three available in flight, because they are restricted to the relatively narrow taxiways and runways, and because so many airplanes, ground vehicles, and ground personnel operate in close proximity to each other, the risk of collision is much greater on the ground than in flight. The review team recognized that a Taxi checklist creates another conflict between procedural demands and operational demands. The pilots are expected to pay full attention to the taxi and at the same time pay full attention to the checklist. And since neither of these tasks can be performed adequately in an automatic fashion, they can not be safely accomplished simultaneously. Rapid switches between the two tasks may not be good enough under these conditions and pilots are at risk of overestimating their abilities to multitask. The review team understood that, given cognitive constraints, this concurrent task management situation in reality means that at least one, if not both, of the tasks suffer; either not enough attention is paid to the taxi, or checklist items are not checked as carefully as they should be.

Contemplating these findings from their review of the original procedures, the team proceeded to design new operating procedures to support the pilots by eliminating, as much as possible, the potential traps it had identified in the original procedures.

The new pretakeoff procedure

In designing the new procedures, the review team employed a number of different strategies:

Re-distribution of tasks We saw earlier that the original description in the FOM went from the After Start procedure, to the Pretakeoff procedure and corresponding checklists (Above and Below the Line), and that the call for flaps was the first item of the Pretakeoff procedure, but the verification check of the flaps was the 10th item in the Above the Line subset of the Pretakeoff checklist. In the revised procedures, the team re-distributed the procedural items across the various phases of operation. The call for setting the flaps is now part of a series of memorized steps that are performed after the engines have been started. Specifically, following the confirmation of engine and related systems indications, the first officer is to perform from memory an After Start flow which ends when he places his hand on the flaps lever and announces "standing by flaps!" This announcement serves as an unmistakable trigger for the captain to call for the particular flap setting for the forthcoming takeoff. The FOM specifically states:

- (First Officer) Position your hand on the flap lever and announce, "Standing By Flaps."
- (Captain) Command the planned flap setting. (Example: "Flaps 5.")
- (First Officer) Restate the flap position (Example: "Flaps 5") and set the flaps.
- (Captain) Verify that the flap lever is moved into the proper detent and the flaps are in transit.

Following this After Start flow, the revised FOM goes into a new, Before Taxi checklist with the clear statement that, as the name implies, it is to be executed before initiating the taxi: "the parking brake remains set until the Before Taxi checklist is completed." This checklist now contains several of the items previously contained in the "silent" After Start checklist as well as the Pretakeoff (Above the Line) checklist. The FOM also provides the following guidance: "There is no need to rush this checklist. Reading the checklist at a normal pace will allow the flaps to reach the desired position[8] as the final checklist step 'Flaps' is read." And indeed, the short Before Taxi checklist only lists 7 items and ends with the call to confirm the flaps' position. The FOM then instructs the pilots that once the Before Taxi checklist has been completed, their attention can be turned to taxi considerations, to requesting taxi clearance from ATC, and to the actual movement of the aircraft.

Having already completed the checklist, there are no longer any procedural demands for the crew to handle during taxi out to the departure runway. Furthermore, the revised FOM clearly instructs the pilots that any unanticipated tasks must be verbally coordinated, and that any demanding tasks require stopping the aircraft and setting the parking brake before addressing them. Under the heading of "Managing Intensive Tasks During Taxi," the revised FOM uses the following language: "(first officer) If unexpected changes require significant flightdeck tasks (for example, FMC programming for a runway change), inform the captain and receive verbal acknowledgement." And it directs the captain in clear terms stating: "(captain) If flightdeck-intensive tasks need to be performed, stop the aircraft and set the parking brake." The FOM goes further to say that "If the reported visibility is less than 4000 RVR,[9] or 3/4 mile, any flightdeck-intensive tasks, by either pilot, will be performed with the aircraft stopped and the parking brake set." As for flaps, the FOM is very specific and directs the captain that if revised performance calculations (as in the case of weather or runway change) require a new flaps setting, the captain must "stop the aircraft, set the parking brake, reset the flaps, and re-accomplish the Before Taxi checklist." In short, based on a thorough analysis of the nature of the operations and the nature of the procedures, the revised FOM *anchors* the timing of the critical action of setting the flaps for takeoff and provides the crew with a robust cue for doing so.

In revising the taxi portion of the FOM, the review team made a first effort to prevent, or at least alleviate, conflicts between procedural demands and operational demands by redesigning the basic procedure, and by providing explicit guidance on how to deal with specific situations that may threaten the integrity of that procedure. In the new FOM, executing the Pretakeoff checklist is no longer competing with taxiing the aircraft for the crew's attentional resources; the need for concurrent task management is reduced, and the opportunities for the prototypical error situations to arise are also significantly reduced. This change turned out to

8 It takes time for the flaps to transition from one position to the next, after the flaps handle has been moved by the pilot in the cockpit.

9 RVR stands for Runway Visual Range which is measured electronically at specific points along the runway. RVR is distinct from "visibility" which is measured (or estimated) from the control tower.

be consistent with official guidance that appeared a year later, urging operators to avoid all checklists while taxiing (FAA, 2003).

Trimming of the checklist As mentioned earlier, the length of the Pretakeoff (Above the Line) checklist increased exposure to interruptions and distractions while conducting the checklist during the busy Taxi phase. The opportunity to be interrupted while performing the checklist was significantly reduced simply by shortening the checklist from 18 items in the original Pretakeoff (Above the Line) checklist, to the revised 7-item Before Taxi checklist.[10] This shortening of the checklist was made possible by reviewing each checklist item separately and re-evaluating its criticality and reason for being on the checklist. In doing so, the team discovered that some of the original items in the Above the Line portion were no longer relevant due to upgrades in equipment, and that some items could be moved to a new, Before Push checklist which is executed just prior to pushing the aircraft away from the gate, a static position with a low risk of interruptions. The opportunity to be interrupted was reduced even more by also performing the whole Before Taxi procedure and completing its related checklist prior to any aircraft movement. That particular time—after the cockpit door is closed, the cabin secured, the aircraft has been pushed back from the gate, the engines started and the pushback crew released, and prior to requesting a taxi clearance from ATC—is a very quiet time that is indeed under the complete control of the flight crew. With a much smaller chance of being interrupted, there is also a much smaller chance of having unanticipated new tasks arise under the revised procedures compared to the original procedures. Thus, two of the four prototypical situations are, to a large degree, avoided.

Re-consideration of operational factors The revised FOM no longer mentions the traditional guidance to taxi with flaps retracted in icing conditions. A careful check with the aircraft manufacturer and with historical records revealed that this guidance was a relic from older aircraft designs that had been carried over through the years. The wing surfaces of older airplanes were indeed susceptible to contamination from ice, snow, or water on the taxiway surfaces, as described in the original FOM. The Boeing 737, however, have enjoyed various design improvements including some to the landing gear and to both leading edge and trailing edge lift devices. As a result, taxiing these new models in slush or standing water during periods of low temperatures no longer poses any risks to the flaps or the slats. Thus, in operating this type of aircraft, it is acceptable to set the flaps in the normal practiced sequence of events under all conditions, and to taxi with flaps set for takeoff even if operating in icing conditions. With their commitment to truly start from scratch and to question received traditions, the review team was able to avoid another prototypical error-inducing situation, that of being forced to defer critical actions and having to remember them later.

10 The original Below the line items have remained largely unchanged under the revised header of the Before Takeoff Checklist.

Anchoring floating items We showed above that a floating item is a prospective memory task by its very nature, and as such is highly vulnerable to being forgotten. The team eliminated floating items and firmly anchored single actions and even entire procedures in the revised FOM. Attaching the call for flaps to the end of the After Start flow is an example of anchoring a single action. Having pilots execute the whole Before Taxi checklist with the parking brake set, prior to any aircraft movement, ascertains that the procedure is now firmly anchored with strong external cues that cannot be easily obscured. The very change of the name, from “Pretakeoff” to “Before Taxi” is an explicit reminder of that anchor. Similarly, throughout the revised procedures, checklist titles make it clear that the purpose of the procedure and associated checklist is to confirm that the aircraft is properly configured for the upcoming phase (e.g., Before Push, Before Taxi, Before Takeoff, Before Landing) and that the appropriate procedure and checklist are to be accomplished immediately prior to commencing that phase.

Facilitating crew coordination The review team also noted lack of crew coordination as the source of many operational errors, so it strived to achieve better crew coordination under the revised procedures than was likely under the original procedures. In our cockpit observations, using the old procedures, it was common to see the captain initiate the taxi and then call: “Flaps 5, Pretakeoff checklist when you are ready!” The call indicated that the captain was aware of the fact that the first officer was still busy with other tasks. Although the call might appear to show consideration on the part of the captain, it was, in fact, an added source of workload (and indirect pressure and stress) for the first officer at a time when the latter was often already very busy catching up for operational reasons beyond his or her control, and rushing to complete earlier, pending tasks. Under these circumstances, the call was not always heard, and the flaps were sometimes not set, or set to a default value rather than the one earlier calculated for the particular flight. In contrast, the revised procedures allow the first officer to set the pace. Although it may appear strange to have the first officer set the pace of the operation, rather than the captain, in this particular phase of the flight, immediately following the starting of the engines, the first officer is the crew member who is most task-saturated and as such, the “weak link” in the chain, hence the one who should be allowed to set the pace for the whole crew. When the first officer, using the new procedures, announces “Standing By Flaps,” it is clear that the first officer is ready to hear the flap setting, and this announcement also serves as a powerful cue for the captain to call for the flaps.

Additional safeguards In the original 18-item Pretakeoff (Above the Line) checklist, the Wing Flaps item was number 10 in the sequence. As is well known from research on memory, the items in the middle of a list are those most likely to be forgotten (Crowder and Greene, 2000; Healy, Shea, Kole, and Cunningham, 2008), compared to items in the beginning or the end of the list. Thus, items in the middle of the checklist are those most likely to be omitted. And of course, the longer the overall list, the more "middle" items are likely to be omitted, given working memory capacity limitations (Barshi and Healy, 2002) (Some caution is required in extrapolating this research to the situation of executing highly-practiced checklists.) Also, the longer the list, the greater the risk of interruption.

The review team provided additional safeguards against accidental omission of the critical flaps action: in the much shorter 7-item Before Taxi checklist, setting the flaps is number 7. The final item is more likely to be performed than a middle item in any list. Recall, also, that movement of the lever to extend the flaps occurs when the captain calls for this action, right before the Before Taxi procedure and checklist. Consequently, placing this action last on the checklist allows sufficient time for the flaps to reach their intended position and for the various indicators to clearly show it. So not only is the basic execution of the task more likely, for the reasons we saw above, but confirmation of the execution through the use of the checklist is also better secured under the revised procedures than it was under the original procedures.

Beyond the Pretakeoff checklist, the revised procedures incorporated yet two more verification steps for the flaps. Under the "Approaching the Departure Runway" section, the revised FOM includes the following:

> "(Captain) Approximately one minute before departure (about 2000 feet taxi distance remaining or # 2 in the departure sequence), …
> Check the aircraft configuration.
> Perform a visual scan of the planned flap setting and stabilizer trim. Ensure that the speedbrake lever is in the forward and down detent."[11]

The FOM then goes on to say:

> "(Captain) With the parking brake released, momentarily advance one thrust lever from idle to midrange and back. Check that the takeoff configuration warning horn is not activated."[12]

These two additional layers of defense against errors of omission further reduce the possibility of the crew being surprised on the takeoff roll.

It is worth noting that advancing a thrust lever as a quick check prior to takeoff to make sure that the warning horn doesn't sound was a technique we observed pilots perform, prior to the work of the review team. As was mentioned earlier,

11 These three items of the takeoff configuration, flaps, trim, and speedbrake are wired to the Takeoff Configuration Warning Horn which would activate upon throttle advancement if not properly set for takeoff.

12 This so called "throttle burst" works on aircraft whose takeoff configuration warning horn is linked with thrust lever position. Some variants of the Boeing 737 aircraft do not have the same feature and for this reason there are air carriers that have added a takeoff warning test button that performs the same function prior to departure.

part of the team's effort was to collect such techniques from the pilot group, and to assess their usefulness. When appropriate, as in this case, these techniques were incorporated into the new procedures. By doing so, the team availed itself of the experience and expertise of the whole pilot group, as well as increased the likelihood of the changes being accepted by the pilots.

In summary, the revised taxi procedures significantly reduced the opportunity for the four prototypical situations that are conducive to error. By performing the procedure during a quiet time and by shortening the length of the checklist, the opportunity for interruptions and distractions is reduced. And by reducing the opportunity for interruptions, the chances of unanticipated new tasks are also reduced. By separating procedures and checklists from the operational task of taxiing, the crews no longer have to perform multiple tasks concurrently. And by eliminating the requirement to taxi with flaps retracted in icing conditions, there is no longer any need to perform a task outside of the normal, practiced sequence of the procedure. What's more, by anchoring the procedure to a specific time and place, it is no longer a floating item. By taking all these steps, the revised procedures eliminated, to a large degree, the need for concurrent task management and for prospective memory, thus greatly reducing the opportunity for error.

Crew performance during the Taxi phase was measured in several cycles of evaluation, first using the original procedures, and later the revised procedures, during both their design phase (to test different versions of the suggested revisions), and at various time intervals following their implementation. With the revised procedures, the number of attempted no-flaps takeoffs was reduced to zero,[13] and throughout flight, the overall number of errors was dramatically reduced.[14]

We used the discussion of setting the flaps for takeoff as an illustration of the approach taken by an airline team for the review, analysis, and revision of that organization's normal procedures. The review team applied the same process throughout all phases of flight to eventually produce an entirely new set of normal procedures, and the outcome was met with similar success (Barshi, et al., in preparation). Recognizing and avoiding the circumstances leading to any of the four error-inducing prototypical situations was one of the main principles that guided this revision process. And this recognition was rooted in the careful analysis of the daily operations and the procedures designed to guide those operations. The

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13 Since those measurements were taken, a few cases of attempted no-flaps takeoff occurred. All these cases were found to be instances of pilots intentionally violating the requirement to perform the Before Taxi checklist with the parking brake set and prior to any aircraft movement. The overall number of these cases is still significantly lower than it was under the original procedures, and further efforts are being made to educate pilots on the consequences of such choices to violate the procedure.

14 It is important to remember that the revised procedures include other operational, engineering, and cognitive aspects beyond those relevant to concurrent task management and prospective memory. We only provided here the details that were most closely related to the theme of this book.

key to reducing errors of omission was to minimize the need for concurrent task management and for prospective memory tasks.

Aviation and Beyond

The work of this team can serve as a model for any organization wishing to support its operators in their job and to reduce the likelihood of inadvertent errors. The considerations used in assembling the team, the methods used for review of existing procedures and practices for identification of error-conducive situations, and the process followed for guarding against them can be applied to almost any type of operation. In the remainder of this chapter, we step away from the particular review process and discuss additional, general guidelines for reducing the likelihood of error in operations. Once again, although the details of the examples are taken from aviation, the underlying principles apply to all work domains involving complex human performance.

Improving the effectiveness of checklists and crew monitoring

Checklists have long been used as a defense against errors of both omission (prospective memory errors) and commission (e.g., mis-setting control trim before takeoff). But the use of checklists is itself subject to error. As pointed out previously, entire checklists or sections of checklists may be inadvertently omitted, especially if conducted when other tasks are competing for pilots' attention. Another insidious vulnerability occurs because pilots execute checklists so often that their performance becomes automatic rather than fully attentive. The verbal response to a checklist item (read aloud by the other pilot) is so habitual that it is often uttered before the pilot's eyes can turn to the item checked to assess its status. Expectation bias (Austen, and Enns, 2003) also operates here—because the item checked is almost always in the expected position or condition, the pilot sees it that way even on the rare occasion when it is not. The combined effects of insufficient attention due to automaticity and distraction by concurrent task demands can lead to inattention blindness or to "looking without seeing" (Simons and Rensink, 2003). It is not unusual for a pilot to direct her gaze to a gauge, for example, and read the expected or normal value rather than the indicated value when it differs from the expected one. Furthermore, having flown a particular model of aircraft thousands of times, perhaps even several times previously that same day, pilots may confuse the present occasion with previous instances in which the item was checked. In general, because fast, fluid execution of procedures is an overall hallmark of expertise and is emphasized in training, pilots do not necessarily recognize that relying on automaticity rather than on full attentive processing reduces the reliability of checklists.

Checklists are used by human operators in many work domains. Improving and maintaining checklist reliability can be achieved if operators force themselves to check each item in a slow, deliberate manner that allows attentive processing. Pointing to or touching each item checked and withholding the verbal response momentarily aids this process. It does take some effort to make this pattern one's habitual manner of performing checklists, because it runs counter to automatic processing that dominates unless kept in check. It also takes self-discipline because operators are often under time pressure, and rushing is a normal human response to time pressure. However, rushing a checklist saves at best a trivial amount of time but enormously increases vulnerability to error. Organizations can help their operators in this matter by carefully deciding when checklists are to be run and by providing formal guidance and training on how checklists are to be executed (see Dismukes et al., 2007 for more detailed discussion of checklist effectiveness in aviation).

Another defense against errors makes use of the fact that work is most often accomplished by teams, not single operators. Transport aircraft cockpit, for example, are occupied by more than one pilot. The concept of crew monitoring in aviation holds that each pilot has a formal responsibility, in addition to all other duties, to cross-check crucial actions of the other pilot and to periodically assess the flight path of the aircraft and the status of its systems (Sumwalt, et al., 2002, 2003). For example, when the captain is taxiing the aircraft the first officer should monitor to ensure that the aircraft is correctly following the assigned route, that conflicts with other aircraft do not occur, and that the aircraft does not enter or cross a runway without a clearance to do so. As with checklists, however, monitoring is also vulnerable to lapses. Organizations can mitigate these lapses by formally describing in their operating manuals what is to be monitored and how, and by treating monitoring as an essential task rather than as secondary. It is worth noting that many airlines now designate the pilot who is not flying a particular leg the *monitoring pilot* (as opposed to the older designation of "pilot not flying"). Training is also required to make operators aware of the importance of monitoring and how to conduct it effectively (Ibid).

Strategic management of concurrent task demands

In Crew Resource Management (CRM) classes, pilots are taught techniques for managing workload that to some degree can help with concurrent task management. Pilots are cautioned to be alert to signs of overload: feeling rushed or confused or getting "behind the airplane." When they experience these symptoms, pilots are shown how to ameliorate the situation by distributing tasks among crew members so that no one person is disproportionately loaded, or by negotiating with ATC for extra time (e.g., delaying taxi on the ground or requesting a holding pattern in the air). Also, when it is simply not possible to accomplish everything they are expected to do, pilots should strategically assess which tasks are most crucial and then defer or omit lower priority tasks in order to focus attention on those that are essential.

The concepts of CRM have been adapted to various other domains, such as medicine, and operators in these domains can adopt similar strategies to deal with overload. But, as we have explained, concurrent task demands create vulnerability to error even when operators have enough time to perform all tasks. Thus, we recommend that CRM training be expanded to include the issue of concurrent task management and to provide specific techniques operators, as individuals and as a team, can use to reduce associated vulnerability to error, especially errors of omission, when confronted with any of the four prototypical situations. Some such techniques are described in the next section.

Training and personal techniques

Good procedures can go a long way towards reducing the opportunity for error. But the operational environment is ever dynamic and will always have a certain level of unpredictability associated with it. Crew members will never be able to rely exclusively on procedures, however well-designed, and must therefore be properly trained and adequately prepared to handle unexpected circumstances with the same level of safety as they handle routine operations. What's more, there will always be some situations in routine operations that require concurrent task management and that present prospective memory tasks, regardless of the careful design of procedures. Thus, besides the thorough design of procedures, explicit training is another key to reducing error in operations.

To assist in avoiding errors of omission, such explicit training must include learning to recognize the circumstances conducive to making these errors, especially those that arise from the prototypical situations discussed in this book.[15] This training should also include strategies for forming clear explicit intentions and strong retrieval cues for any prospective memory tasks, as well as for developing the habit of performing a deliberate search for any incomplete procedure or deferred intention at regular intervals during the operation. Further, this training should include both the principles we have discussed and concrete examples relevant to the specifics of the given operation, so operators can understand how the principles apply to their daily work.

Training and procedures go hand in hand in supporting all operators. For example, the last item in the Before Takeoff procedure mentioned above, the "throttle burst" prior to taking the runway to make sure that there are no conditions, such as flaps not extended, that would activate the takeoff configuration warning horn, is akin to stopping at the door prior to leaving the house to ask "do I have everything I need?" Some people check to make sure they have the keys before shutting any door that locks behind them. Similarly, a periodic deliberate check for

15 Learning to recognize factors ("threats") that could jeopardize the safety of a flight is at the heart of Threat and Error Management (TEM) training programs (Gunther, 2004; Veillette, 2005), though this training does not focus specifically on situations that make demands for concurrent task management and/or prospective memory.

deferred intentions or other forgotten items is critical in searching for anything that might have slipped through the multiple layers of defense built into the design of systems and procedures. "Are we forgetting anything?" "Have we been interrupted in the middle of anything that we should have resumed?" "Have we been focusing our attention for too long on a single aspect of our workload or the environment?" "Are the circumstances we are in similar in any way to any of the prototypical situations conducive to error?" These are the kinds of questions operators must learn to ask on a regular basis throughout routine operations to avoid the traps that we (and they) know are out there. An especially crucial time for pausing to check for uncompleted actions is at transitions from one phase of operation to the next, for example, before taking the runway for takeoff, when leveling off from climb or descent, before starting a landing approach, and when exiting the runway after landing.

Asking these kinds of questions forces the brain to search memory for deferred intentions relevant to the current situation. But that search is likely to be ineffectual if the individual has not explicitly encoded an intention to perform the deferred action at a later time. Pilots, like all individuals, often fail to encode intentions adequately in memory because of time pressure or the abruptness with which interruptions seize attention. Individuals may also fail to recognize that remembering habitual tasks is no longer reliable when performed outside the normal sequence of procedures, and thus requires encoding an explicit intention both for the fact that there is a deferred task, as well as for *when* the deferred task is to be performed.

Under routine circumstances, operators don't usually encode intentions for deferred tasks so explicitly, rather they implicitly rely on environmental cues, their expertise, and the nature of the operation to remind them. This approach works often, but not always. Unfortunately, the many times when individuals successfully remember to perform deferred tasks may lead them to underestimate their vulnerability to forgetting, and hence to not develop a habit of explicitly encoding intentions to complete the tasks later. Most people's personal experience[16] clearly shows that this approach can fail. ASRS and NTSB reports reveal that the danger and consequences of forgetting are substantial; thus explicit strategies to boost prospective memory performance are essential.

One such strategy is to create the operationally relevant equivalent of a "sticky note" (e.g., a Post-it® note). This type of note provides two key ingredients for reliable recall: it explicitly registers the intention in memory and it serves as a clear cue for its retrieval. However, the cockpit and most operational environments do not always support the use of the paper sticky notes; the operators must be creative in finding the best approximation to a sticky note to meet both goals: clear

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16 We have all been in situations where we found ourselves saying "I can't believe I forgot to do it!" This expression shows that we intended to perform a task at some point later than the time at which we thought of it, and assumed that we would remember it at the right time, but didn't.

encoding and strong cueing. In our observations and in informal conversations with pilots, we came across many personal strategies aimed at doing just that. When pilots encounter a situation in which they know they are at risk of forgetting to do something later (namely, an obvious case of a prospective memory task), they often employ their own equivalent of the sticky note. They may, for example, place the checklist card between the throttles to serve as a reminder that the checklist was interrupted, or place an empty coffee cup on the landing gear handle to remind themselves of their decision to lower the gear at a later point than usual, or hold their fingers crossed as long as they were cross-feeding fuel to remember to return the fuel pumps to their normal configuration. These creative cues are conspicuous and distinctive and have the added advantage of physically preventing the pilot from taking downstream actions before performing the deferred task.

Creating cues, however, only works for operators who are acutely aware of the deferred task, of their vulnerability to forgetting to perform this particular deferred task, and of the fact that no reliable cues other than this strategy were available. The failures we have been presenting throughout this book are cases in which pilots were probably not as aware of their vulnerability to forgetting. Again, explicit training which is focused on these situations and which provides guidance and opportunities to experiment with such strategies could help increase operators' awareness of these potential traps, and in providing them with strategies to avoid them. Research is needed to develop the most effective training strategies.

Managing fuel in flight is a good example of a prospective memory task that could be used in pilot training (if relevant to the particular airplane model). Slight differences in performance between an aircraft's two engines sometimes lead to a fuel imbalance, which requires cross-feeding. Normally, each engine draws fuel from its respective wing tank; that is, the right engine draws fuel from the right wing tank and the left engine from the left wing tank. If, for example, on a given flight the left engine uses slightly more fuel than the right engine, then over time the right wing will become heavier with the greater amount of fuel remaining in the right wing tank compared to the left wing, and induce a right roll moment (i.e., the aircraft will roll to the right). If left unattended, this situation could compromise aircraft control. Thus, it is critical to correct this fuel imbalance, and this correction is done by rerouting the fuel flow such that the left engine also draws fuel from the right wing tank. This cross-feeding of fuel is maintained until the two wing tanks are equal again, and then it must be stopped lest the imbalance again occurs but in the opposite direction.[17]

17 Some times, the pilot may choose to cross-feed for a bit longer than just the equal point and intentionally create a small imbalance in the opposite direction with the expectation that the difference in fuel consumption between the two engines will bring the tanks back to the equal point and reduce the number of time cross feeding would be necessary.

Once cross feeding has been initiated, remembering to return the fuel pumps to their normal configuration when the fuel imbalance is corrected becomes a prospective memory task. The deferred intention requires a periodic scan of the fuel system panel to maintain awareness of the progress of the fuel balancing process. However, due to its location on the overhead panel above and behind the pilot's head means that it is not always part of their frequent scanning of the flight and engine instruments. The fuel gauges are on the center instrument panel, but even they are in the area between the two pilots such that they are not right in front of either pilot's eyes. In other words, monitoring the fuel balancing process requires an intentional shift of attention that is not part of the pilot's habitual scan of cockpit displays. If the aircraft is on descent to its destination and the engines are idling, it may take a long while before balance is restored. It is very difficult to maintain the intention to stop the cross feeding over such a long period of time, particularly because many other things are happening during that time that distract the pilot from maintaining the intention in her focus of attention. In short, stopping the cross feeding becomes a deferred task that cannot be eliminated by a well-designed procedure, and the pilot is back to a prototypical error-prone situation, that of having to interleave the task of monitoring the status of the fuel gauges periodically with other tasks ongoing in the cockpit at the same time.

Unfortunately, it is difficult to maintain this sort of periodic monitoring—individuals are vulnerable to getting caught up in the other tasks and forgetting to monitor. Scientific research has not yet provided specific techniques to maintain monitoring in these situations, however, the general techniques applicable in all prospective memory situations can provide a fair degree of protection. If the pilot was well trained to recognize prospective memory situations, then he would know the importance of clearly encoding the intention in memory, and of creating a strong cue for the retrieval of the intention. The pilot might, for example, involve the other crewmember in the task. Something as simple as "don't let me forget the cross feed!" increases the chances of recalling the intention.

Summary of Recommendations

For organizations

Organizations can easily adopt and adapt the approach taken by our collaborating airline in reviewing and revising procedures. Starting from scratch and questioning everything is an excellent way to uncover implicit assumptions and unrecognized vulnerabilities to error. It is crucial to thoroughly analyze reported and observed problems in routine operations, and to go beyond their surface manifestations to identify, and understand the true nature of the problems encountered with existing procedures prior to designing and implementing new procedures. Likewise, it is critical to perform a careful analysis of the procedures, the training, and of the actual operations to identify underlying assumptions, and to characterize the discrepancies between the ideal and the real operating environment. This analysis should identify situations in which procedural demands conflict with operational demands. It should also identify the ways in which the four prototypical situations manifest in the particular type of operation. Moreover, the analysis must identify the ways in which the given procedures might lead to such situations, especially those in which:

- operators are likely to be interrupted or distracted, as well as other situations that lead to prospective memory tasks,
- tasks may not be executed in their normal practiced sequence,
- unanticipated tasks are likely to arise, and
- tasks must be performed concurrently.

Once the analysis has been completed, the organization can turn to redesigning the procedures to avoid these situations, and to creating multiple layers of defense; the more critical the item, the more layers are needed. Specifically, the procedures should minimize the need for concurrent task management and for prospective memory tasks. The redesign should consider anchoring all floating items, shortening and grouping procedures, identifying or creating quiet points in the timeline of an operation to execute procedures to completion, and removing as many conflicts between procedural and operational demands as possible.

In addition to aligning the procedures with the reality of the operation and the characteristics (strengths and vulnerabilities) of human operators, the training should also reflect the real, rather than the ideal situation. It should provide guidance for successfully handling prospective memory and concurrent task management situations. Operators should be explicitly trained to recognize the circumstances that are conducive to error (e.g., the prototypical situations and how they manifest themselves in the particular operation) and how to avoid and/or manage them. The training must emphasize that when operators have to defer a task, it is almost always necessary to attend to other tasks during the period before the deferred task can be performed, and that because attention is focused on these other tasks, the intention to perform the deferred task at the appropriate time cannot readily be maintained in working memory and is likely to slip from awareness. Operators must be led to realize that the great challenge of prospective memory tasks is recalling the deferred intention at the appropriate time, because typically there are no prompts to alert them that the appropriate time has arrived—they must somehow "remember to remember." Training can help operators increase their chances of accurate and timely recall by providing strategies for explicitly encoding deferred intentions and for creating strong retrieval cues.

Procedures are seen as representing the safest, most efficient way of performing work under relatively benign conditions. However, complex operations by their very nature cannot be scripted with perfect reliability. As the Real Chapter clearly shows, routine operations are highly dynamic and unpredictable, even if within predictable bounds. Thus, it is not possible to have a procedure for a given task that would work under all conditions, in all situations, and for all operators. It is not even desirable to attempt to cover all of the known exceptions, because it would require unmanageably large FOMs. Given that some situations may fall outside the scope or language of the available procedures, operators must be trained to recognize that these situations will increase the likelihood of error. They must learn to appreciate that, even when equipped with procedures that have been well designed, there will be times when they will be called to devise ways to flexibly but safely accommodate operational demands. Training should help operators to recognize, accept, and appreciate their own vulnerabilities, and to develop effective and safe personal strategies. Organizations may choose to require operators to route such strategies through appropriate channels for evaluation and possible formal implementation.

Beyond helping operators best deal with the reality of the operational environment, organizations should also take the time to examine whether the organization's own priorities and the ways those priorities are implicitly or explicitly promoted exacerbate the complexity of that environment. Organizations must recognize and address the ways in which operators are implicitly pushed to compromise safety by the inherent tension between safe operations and production pressures. Production pressures in aviation (e.g., on-time performance, cost savings) show up in forms such as short turn-around time at the gate, publications comparing on-time arrivals with those of other airlines, and emphasis on the increasing costs of fuel. Air traffic control conveys its own production pressures in last minute runway changes and in "slam-dunk" approaches (which are situations in which arriving flights are kept high until very close to the airport to facilitate traffic flow, and then instructed to make steep descent to a landing). These pressures, combined with others created by social and legal concerns create situations in which workload and concurrent task demands are high. Crews often respond by rushing, which further increases the vulnerability to error associated with concurrent task management. Organizations should examine both their formal guidance and their implicit reward structures to encourage operators to strike an appropriate balance between production throughput and careful, deliberate management of tasks. In many cases, explicit guidance about how the organization expects the operators to safely handle conflicting demands is sufficient, provided the organization's structure for rewarding and reinforcing operator performance is consistent with that guidance.

Checklists and monitoring are crucial defenses against errors and equipment failures, but in practice these defenses are often not fully effective because operators unwittingly slip into automatic rather than attentive execution. Companies can bolster these defenses by providing training on the nature of this vulnerability and by providing formal guidance on how checklists and monitoring in deliberate and fully attentive ways should be performed.

Finally, for any organization contemplating revising operational procedures to help operators avoid errors, we emphasize the importance of collecting data on its operators' performance, both before and after any changes. Continuously evaluating the effectiveness of procedures and training, and continuously monitoring for the occurrence of errors and deviations are central to the health of any organization.[18] Evaluating the success of any procedural or training redesign is important for the identification of any unintended consequences arising from the implementation of changes.

For individuals

Individual operators can, in addition to encouraging their organization to adopt the recommendations listed above, develop their own personal techniques to reduce the risks associated with prospective memory tasks and with concurrent task management. You can learn to recognize the prototypical situations in your work, and realize that you are especially vulnerable to forgetting anytime you are interrupted, have to manage concurrent tasks, or when anything forces you to deviate from the ideal or habitual flow.

Recognizing the ways in which the prototypical situations manifest themselves in your own work environment can help you develop techniques to prevent them. For instance, recognizing the risks associated with interruptions can lead you to be very careful when you have to interrupt somebody else, and to adopt a strategic approach to letting yourself be interrupted. Such an approach will help you decide when to attend to an interruption after explicitly encoding your place in the interrupted task, or when to hold off the interruption until the current task gets to a good stopping point. Similarly, recognizing the need to respond to several different demands at once, you can call on a co-worker for help, or offer your help when you see somebody else in that situation.

Regardless of formal training, you can practice associating intentions for deferred tasks with strong external retrieval cues. When forming these explicit intentions, it is important to identify the time or circumstances when the deferred intention should be performed and to identify or create specific cues that will be present at the appropriate time. In other words, determine and set your work environment equivalents of the sticky notes, making use, when appropriate, of any alerting devices (alarm clocks, timers) that are available to you. You can also practice periodic, deliberate searches for incomplete tasks and for deferred intentions, something which can prove useful in your home environment too, not just at work. Deliberate searches are particularly useful in the transition points between distinct phases of an operation, and following interruptions. Practice can help make this deliberate search a habitual action that can better persist even in time-pressured and otherwise stressful situations. Last, but not least, you can also develop the habit of enlisting your co-workers to help with prospective memory tasks, for example by letting them know when you are deferring a task and/or by

18 Examples of guidelines for evaluating whether "best practices" have been successful in reducing errors in other domains can be found in the literature, e.g., Rogers, Cook, Bower, Molloy, and Render, 2004 (wrong-site surgery).

asking them to help recall it later, and by inviting them to also perform a regular "sweep" for incomplete or deferred tasks.

It is important for you to realize the ways in which organizational pressures affect your workload, and may create error-inducing situations. Your vulnerability increases with increases in workload and time or production pressure, or in off-nominal operational conditions, as well as under conditions of fatigue or stress. So it is best to develop a strategic approach to the management of workload, one that doesn't devolve into a reactive mode when workload increases. Traditional CRM measures are relevant here: prioritize, delegate tasks, reduce task demands, shed tasks, and buy time when possible. It is tempting to try to comply with production pressures, but you must remember the dangers of rushing and the vulnerability to error under these conditions. To mitigate these dangers, avoid deferring critical tasks to the extent possible, and discuss your plans with your team members. For instance, when you must defer a task, identify exactly when to perform the task, the cues that will be available, and how the deferred task will fit in with tasks ongoing at that time. In short, build your own defense layers against the prototypical situations conducive to error, whether they are brought about by organizational pressures or by the reality of the operation.

Concluding Thoughts

We have drawn upon recent research in cognitive psychology, especially in prospective memory, to suggest ways in which the challenges of concurrent task demands can be better managed and vulnerability to omitting intended actions can be reduced. Although in this book we emphasize safety, these measures are equally relevant to efficiency and cost. For example, although we know from ASRS reports that failure to set flaps before attempting to take off occurs on a monthly basis in the airline industry, in almost all instances the takeoff configuration warning horn alerts the crew to abort the takeoff safely. But rejected takeoffs impose significant fuel and time costs—in some of these instances, the crew must taxi off the runway and allow the brakes to cool, thereby delaying the flight even further. Other industries could improve the efficiency as well as the safety of their operations by adopting measures comparable to those we have described for aviation.

We are confident that the measures we suggest will be effective if applied thoughtfully and diligently, but these are by no means complete solutions. Considerably more research is required in many areas to develop powerful countermeasures. For example, as far as we know, no research is being conducted to devise ways to help operators who must interleave multiple tasks with novel content that requires attentive processing. This can be attributed not to lack of interest on the part of scientists, but to the paucity of research funding for this sort of inquiry.

It is also crucial to recognize that operator error cannot be fully understood in isolation. The organizational environment and the operational environment play critical roles in creating the circumstances that lead to error. We must recognize that procedures and training that are based on the assumptions of the ideal operating environment are not helpful, since operators out in the field have to face the complex reality of the operation and the discrepancies between the ideal and the real examined in the early part of this book. Not only must the procedures be designed with a thorough understanding of the complexity of real world operation and the strengths and vulnerabilities of the real operator, but also the training must reflect that understanding. Part of this understanding is recognizing the ways in which the prototypical error-conducive situations manifest themselves in the particulars of the given operation. Another part is recognizing how the performance of individuals and teams is affected by the inherent characteristics of human cognition, organizational factors, and the interaction of these factors with cognitive characteristics.

Aviation operations are very carefully scripted in explicit procedures and manuals. These written records facilitated our analysis and enabled us to demonstrate the discrepancies between the ideal setting and the real operational environment. But medical operations, and operations performed by nuclear power plant workers and by train engineers, and by countless other professionals in their work environments are all susceptible to the same discrepancies and to the same errors. The examples taken from everyday life in the Preface and Chapter 2 (Multitasking) clearly show that even simple aspects of personal life show the same vulnerabilities to forgetting deferred intentions and to the challenges of concurrent task management. The operation of a cell phone while driving, or the intention to return to the food that is cooking on the stove after chopping some additional ingredients may not be as exciting or as critical as remembering to extend the flaps before pushing the throttles of a large jet aircraft for takeoff, but they tell the same story. What's more important, the strategies for reducing error in flight operations can be just as useful in everyday life as in all systems requiring high reliability.

All operators are vulnerable in similar ways. Unfortunately the myth that one can multitask without degrading performance and risking accidents is all too prevalent in modern life. Inadvertent errors of omission are generally not careless oversights, nor are they evidence of lack of competence or of conscientiousness. The reality is that cognitive constraints on attentional resources, on the ability to manage concurrent tasks, and on prospective memory are shared by all people everywhere, in all endeavors.