Docket No. SA-509

Exhibit No. 14C

NATIONAL TRANSPORTATION SAFETY BOARD

Washington, DC

DECISION-MAKING IN THE COCKPIT
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Cockpit Resource Management

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Academic Press, Inc.
Harcourt Brace Jovanovich, Publishers
San Diego New York Boston London Sydney Tokyo Toronto

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Decision-making in the Cockpit

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INTRODUCTION

Cockpit crews make decisions all the time, from the captain's acceptance of the aircraft and flight plan prior to departure to docking at the gate after landing. Unfortunately, the ones that get the most attention are those that result in disasters—for example, the decision to take off with snow and ice on the plane and engine power lower than needed for takeoff at Washington National Airport (NTSB, 1982), or the decision to take off without being sure the runway was clear of traffic in heavy fog at Tenerife, Canary Islands (Dutch Aircraft Accident Inquiry Board, 1979).

While an industry-wide analysis has shown that over 70% of aviation accidents result from crew coordination or communication problems (as opposed to lack of individual technical skills, Lautman & Gallimore, 1987), Diehl has found that over 50% of accident-related human errors in the military and civil aviation industry from 1987 to 1989 were decisional errors (Diehl, 1991). The aviation industry and the U.S. Federal Aviation Administration (FAA) are both concerned with improving the quality of decisions made in the cockpit. The importance accorded cockpit decision-making is reflected in its inclusion as a recommended topic in the revision of the FAA Advisory Circular on crew resource management (CRM) (FAA, in preparation). Decision-making modules are already included in the CRM courses run by most of the major air transport carriers. Another FAA Advisory Circular deals specifically with Aeronautical Decision Making (FAA, 1991). This circular is aimed mainly at general aviation, corporate, and commuter flying, but its concerns about hazardous attitudes apply to all pilots.

Because decision-making takes mental energy and because a large body of research suggests that people do not always make optimal decisions, aircraft builders and flying organizations try to reduce crew decision-making as much as

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possible. This is done by automating systems and by establishing standard procedures and checklists to cover anticipated failures or emergencies (Billings, 1991; Wiener, 1988). However, poor decisions may occur even when situations are fairly straightforward because of the presence of conditions that increase risk, often weather and/or heavy air traffic. In other cases, simple problems cascade or interact, precluding "by-the-book" solutions. In still rarer cases, completely unforeseen catastrophic problems arise, like the loss of all hydraulic systems due to an engine explosion (NTSB, 1990; see the chapter by Kayten). Given the impossibility of designing error-proof or fully automated systems that can cope with any emergency, the only way to maintain or increase safety is to train crews to make the best decisions possible under difficult circumstances. The question is how to do that. What skills should be trained and how should they be trained?

The short answer to these questions is the following: crew decision-making is not one thing. Crews make many different kinds of decisions, but all involve situation assessment, choice among alternatives, and assessment of risk. However, the decisions differ in the degree to which they call on different types of cognitive processes. A decision to abort a take-off requires different decision processes from choosing an alternate airport for landing with a system failure or determining the cause of a master caution warning light. The nature of the processes involved in a decision depends on the structure of the decision task and the conditions surrounding it. How familiar is the problem? Is a response prescribed or must it be generated? How many options are readily available? How clear is the nature of the problem? Is time limited? Given the variety of decisions that are made routinely in the cockpit, no single approach can be prescribed for training crews in decision-making skills. No silver bullet exists to make crews better decision-makers.

The long answer to the above questions is addressed in the five issues that follow. Brief sketches of the topics to be discussed under each are provided below and elaborated in the remainder of this chapter.

✈ ***What is cockpit decision-making?*** Six different types of decisions are made by crews in the cockpit (Cf. Rasmussen, 1983).

1. Rule-based decisions (condition-action rules): (a) go–no go decisions and (b) recognition-primed decisions
2. Knowledge-based decisions (well-defined problems): (a) option selection decisions and (b) scheduling decisions
3. Knowledge-based decisions (ill-defined problems): (a) procedural management and (b) creative problem-solving

These six types of decisions impose different processing demands on the decision-maker and imply different types of training.

✈ ***How can we recognize good decisions in the cockpit?***

1. Good cockpit decisions support effective task performance (judged by safety, efficiency, and effectiveness). Consequently, cockpit criteria are not the same as laboratory criteria, where logical consistency and optimality prevail.
2. Cockpit decision criteria include cognitive economy (least mental effort), working within time limits, and constraint satisfaction.
3. Formal normative decision models do not fit conditions in the cockpit, which are dynamic, reactive, action-oriented, and time-pressured.
4. Cockpit decisions are heuristic. Grounded in expert knowledge and experience, heuristics work most of the time. They are shortcuts that reduce the mental work involved in making decisions and yield decisions that are good enough rather than optimal. Expertise contributes to rapid situation assessment, retrieval of candidate solutions, and guidance based on past experience. Expertise does not, however, insulate crews from bad decisions. It may lead to rigid expectations, biases, overconfidence, and greater risk-taking.

✈ ***How does crew decision-making differ from individual decision-making?***

1. Crew decision-making is managed decision-making. The captain has responsibility for making the decisions but is supported by input from the crew, both in the cockpit and on the ground (air traffic control, dispatch, maintenance).
2. Crews may do *better* than individuals: (a) Multiple eyes, ears, hands, and minds increase available cognitive capacity, increasing the potential for better decisions. (b) Crews can consider a larger picture, contribute more viewpoints, offer multiple options, use more information, share workload, critique proposals, and avoid traps.
3. Crew may do *worse* than individuals: (a) Through poor communication, crews may not share an understanding of the problem or how to go about solving it; they may not understand the captain's intentions. (b) Errors can propagate through the crew, while increasing their collective confidence in their correctness. (c) Crewmembers may abdicate responsibility, leaving work to others, or can perform poorly due to interpersonal conflicts.

✈ ***What ingredients contribute to effective crew decision-making?***

1. Situation awareness: Crews are alert to developing situations, sensitive to cues, and aware of their implications.
2. Planfulness: Crews work out plans and strategies for reaching their goals, prepare for contingencies, figure out what information they need, and evaluate their progress.
3. Shared mental models: Crews communicate efficiently to create a shared big picture: What's the problem? What are we going to do about it? Who does what? Through shared models crews utilize all available resources,

make sure that they're all solving the same problem, and assure coordination.

4. Resource management: Resources are used efficiently and explicitly. Crews set priorities, schedule tasks, allocate responsibilities, and build in thinking time, especially for the captain.

The above four ingredients do not in themselves constitute decision-making, but create a context within which effective decisions can be made.

✈ *Implications for training: What skills should be trained and how?*

1. What to train? (a) Situation assessment: based on considerable pattern recognition practice and development of models of the systems and tasks in the cockpit. (b) Risk assessment: recognizing risk factors associated with various malfunctions and situations. (c) Planning: strategizing, anticipating future events and outcomes of actions, critiquing plans. (d) Resource management: prioritizing tasks, estimating time requirements, scheduling, allocating responsibilities. (e) Communicating: Building shared models for the problems through explicit communication about goals, plans, strategies, expectations, and reasons. (f) Specialized skills should be trained to meet the specific demands of each of the six decision types.
2. How to train? Train crews under time-pressured high workload conditions representative of those under which they will be expected to make difficult decisions.

WHAT IS COCKPIT DECISION-MAKING? ✈

Cockpit decision-making is many things, but all types of decisions have at least three elements in common: choice among options, situation assessment, and risk assessment. First, by definition, all decisions involve choice among alternatives. However, the nature of the choice depends on task conditions. Some decisions do not appear to be choices because only one option is considered (e.g., deciding to descend to a lower altitude following loss of cabin pressure). Sometimes the choice is to stop doing something already in progress (e.g., aborting a take-off or landing). In still other cases, the manner in which an action is performed must be determined (e.g., deciding on a cruise speed when the landing gear will not retract). And finally, the choice may be about the sequence and timing of a set of actions, all of which must be accomplished in a limited time period (e.g., manually lowering landing gear and extending flaps following a hydraulic failure). These various types of choices are considered in this chapter. No one type is more important than any other. However, very different kinds of cognitive work must be done for each of them, as is described shortly. Furthermore, differences in requisite cognitive processes mean that each will be vulnerable

to disruption or increases in difficulty from different sources. Likewise, each requires a specific focus in training.

Prior to making a choice among options, however, the nature of the problem must be accurately assessed. Whereas the choice aspect of decision-making has been the focus of most laboratory research, decision-making in naturalistic situations requires people first to recognize that a problem exists that may require a decision, and then to define the nature of the problem. Based on his observations of decision-making by fire fighters and tank commanders, Klein and his colleagues (Brezovic, Klein, & Thordsen, 1987; Calderwood, Crandall, & Klein, 1987) have concluded that the biggest difference between experts and novices was in their ability to evaluate the situation rather than in their ability to choose among options.

Third, all cockpit decisions involve risk assessment, whether it is explicit or not. Safety is the overriding concern behind every decision, but other values on occasion are pitted against safety considerations. These frequently are subtle pressures resulting from organizational policies and goals. For example, according to a NASA Aviation Safety Reporting System report (ASRS, 1991), one pilot described pressure from the company ground agent after an hour's delay at the gate to depart with an incompletely locked forward cargo door. The agent justified it by saying, "We release planes like this all the time." Certain decisions are programmed as responses to specific conditions to eliminate the need for the crew to assess risk and make a decision, especially in time-critical situations. Some of these are triggers to abort take-offs or landings. But in many cases, borders blur and gray areas emerge in which the captain's assessment of the conditions—visibility, runway conditions, the aircraft, and his own skill—determines the choice of action. Judging by confidential reports to ASRS, pilots are often quite conscious of the trade-offs involved in their decisions. For example, one pilot reported that, following a loss of cabin pressure, he descended to a lower altitude and continued to the original destination. He noted that this decision was not as conservative as landing immediately, but since no passenger injuries were evident, he felt the passengers' convenience would be served better by continuing to the destination than by diverting.

Beyond these three common elements of situation assessment, choice, and risk assessment, the types of decision problems in the cockpit differ in their underlying structure, time parameters, and information characteristics. They require different kinds of mental work and consequently are susceptible to different types of failures. Six different types of decisions have been identified. These are illustrated in the double boxes in Figure 5.1. This figure shows the relationships among the different types of decisions, based on problem definition, information, and option availability. It is not a flowchart of human information processing, but a depiction of decision categories. These six categories differ in the degree to which they call on cognitive components, such as cue or situation interpretation, problem

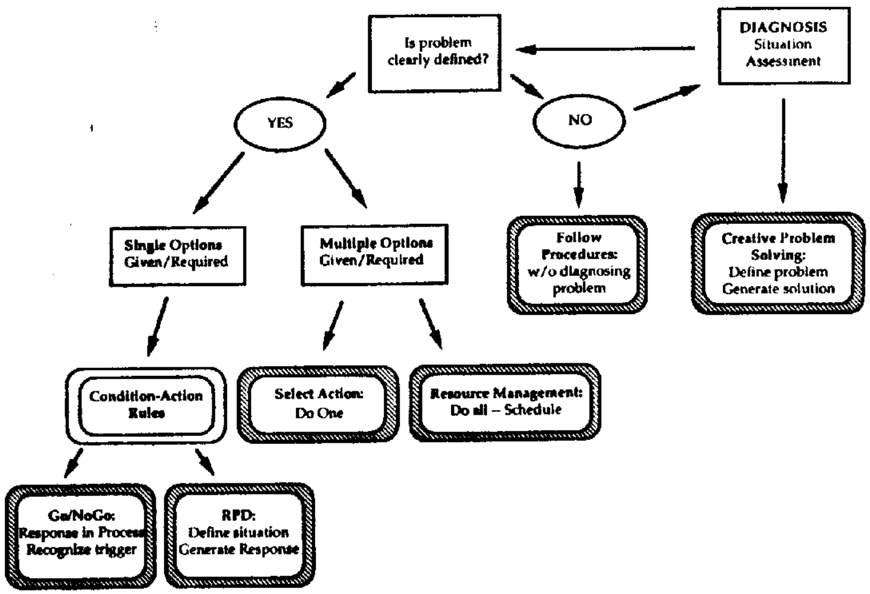

Figure 5.1 Taxonomy of decision types.

structuring, option generation, option assessment, probability estimation, constraint satisfaction, priority setting, time estimation, causal reasoning (diagnosis), risk assessment, planning, forward reasoning, and information integration. This figure will be discussed from top to bottom, left to right.

While various types of decisions can be distinguished for analytical purposes, in practice any given flight situation may require use of several different decision strategies. Making one decision or taking the prescribed action may present a new set of conditions requiring a different type of decision. To an observer, these may appear as a smooth flow of action, although decisions are hidden behind the actions.

Well-defined versus Ill-defined Problems

Most cockpit decisions are triggered by conditions falling outside normal ranges. A light flashes, an indicator drops to the yellow or red range, a strange vibration is felt. Some of these cues are unambiguous in the context and in the phase of flight in which they occur. Any pilot experienced in flying that plane would interpret certain cues to mean the same thing. Many instrument readings fall into this category. The displays of newer planes ("glass cockpits") are even more explicit in telling the crew what they mean. When the problem is clear from

the display or cue configuration, the crew does not need to expend energy trying to discern what it is. We refer to these as well-defined problems. But sometimes displays do not unambiguously indicate the nature of the problem. Then the crew must engage in diagnostic efforts to figure out what triggered the signal or cue. How they do this depends on the nature of the specific signal—whether a checklist exists for addressing that particular problem or whether the crew literally has to fly by the seat of its pants to determine the underlying cause of the signal. This second category is what we mean by ill-defined problems. The highest branch of the taxonomy in Figure 5.1 distinguishes between well-defined and ill-defined problems. Well-defined problems will be described first.

Single versus Multiple Response Options

Given that the nature of the problem is clear, decision tasks differ in the information available about response options. Certain cue sets offer or require just a single response, while in other cases, multiple response options are immediately available or required. Single-response situations in the cockpit appear to fit what Rasmussen (1983, 1993) has called rule-based decisions, while multiple-response problems invoke knowledge-based reasoning. Single-option cases can be defined as condition–action pairs and are perhaps the simplest decisions because they require the least cognitive work. When multiple options are immediately available, as when choosing an alternate airport, choice is involved and additional cognitive work is usually required to select one option from among the set.

Rule-based Decisions

In rule-based decisions, the primary decision is whether circumstances meet the conditions for a pre-set response. Condition-action rules specify that a particular action should be taken when a certain stimulus condition exists. Little reasoning or deciding about the nature of the response is required. Most effort focuses on whether circumstances fit a specified pattern. Two different types of rule-based decisions can be distinguished. In the first case the response is anticipated or already in process and a stimulus condition arises that triggers a decision to terminate that response. These tend to be decisions to reject take-offs or to go around on an approach. This type of decision is called a *go/no-go* decision. In the second type of rule-based decision, the appropriate response must be generated by the decision-maker. It is not already in process but must be generated, evaluated and implemented. These decisions are referred to as *recognition-primed* decisions (Klein, 1989, 1993).

1. *Go/no-go decisions.* In go/no-go decisions, an action is in progress, a pattern is recognized that signals danger, and the response is pre-set: stop the action. The cognitive work that must be done is essentially perceptual and in-

terpretive. The crew must recognize a stimulus configuration as a signal to initiate the designated "Stop" response. No choice of response type is required. However, the stimulus conditions that elicit this response may actually be quite diverse. For example, ASRS reports of rejected take-offs include as triggers explosive engine failures, cargo door lights, runway traffic, compressor stalls, and overheat lights (also see Chamberlin, 1991). Likewise, missed approaches, which consist of a decision to terminate a descent to landing, were most often triggered by inability to see the runway at decision height but were also triggered by traffic (air or ground), autopilot disengagement, and unstable approaches (e.g., off glide slope). Decisions of this type involve risk assessment, particularly when ground speed or altitude are near a decision threshold. Certain conditions, like a wet runway or system malfunctions resulting in poor braking, will complicate the decision and may shift it across the threshold. Decisions in this category are in general the most time-critical because of the severe consequences of mistakes. As a result, this is the type of decision that is most proceduralized. Companies want their crews to act quickly and think as little as necessary in these conditions. However, given the need to assess the risks and interpret conditions that may be changing rapidly, this type of response must clearly be defined as a decision.

2. *Recognition-primed decisions.* The second category of rule-based decisions is what Klein (1989, 1993) has called recognition-primed decisions (RPDs). Like go/no-go decisions, these also involve condition–action pairings. The crew first interprets the cue configuration as a particular type and then generates an appropriate response. The response is not ongoing, as it is in the go/no-go case. According to Klein's research, once the situation has been properly assessed, responses are retrieved on the basis of their past success. In airline cockpits, however, these responses are often prescribed as standard procedures. For example, following loss of cabin pressure, the response is to descend to a lower altitude. Or when the terminal collision avoidance system (TCAS) indicates traffic, the crew attempts to locate the traffic visually, using their TCAS screen as an aid. These two cases require rapid responses. Not all responses in this category are as time-sensitive, but many are. For example, in the case of a fuel leak, the crew must calculate the fuel remaining, the rate of loss, and how long they can continue flying; identify the closest appropriate airport; and perhaps declare an emergency. These tasks must be handled expeditiously, but not in the same time frame as collision avoidance.

The cognitive work that must be done in recognition-primed decisions includes situation recognition, response generation, and response evaluation. Response evaluation involves simulating the consequences of taking the candidate action and determining whether the response will satisfy the crew's goals. If so, the action is accepted. If not, another option is generated and evaluated, or the situation definition is reassessed. Risk assessment is involved in the response evaluation.

Multiple-Option Decisions

The next major category of decisions includes those that are made when the situation is clearly defined and multiple response options are available or required. In one case multiple options are present and the pilot must choose one (*option selection* decisions). In the other case multiple options are present and all must be accomplished within a limited time frame (*resource management* decisions). The first type are true choices and map most closely onto our everyday notion of decision-making. The second type are usually scheduling decisions and involve resource allocation and management. Both are cases of knowledge-based reasoning (Rasmussen, 1983).

1. *Option selection decisions.* On occasion the crew must select one option from among a set of alternatives, meeting certain constraints active in the situation. Cockpit selection decisions often involve selection of an alternate landing site. The conditions demanding such a decision may be bad weather at the original destination or an in-flight problem that requires a diversion. Alternates are prescribed in the flight plan if weather conditions are bad or deteriorating at the original destination and may be needed in the case of a missed approach. For discussion purposes, I deal here with weather-induced diversions. The choice decision process is triggered when the pilot first decides that the original destination may not be suitable for landing (a no-go decision). The decision to abort the landing should generate the alternate, a recognition-primed decision. Consequences of going to the alternate are considered, and if no reason is found to reject it, that option will be accepted and the decision is done.

However, if situational factors prevent a clean decision, conditions such as bad weather at the alternate or an aircraft system malfunction that creates special requirements, such as a long, dry runway, emergency or medical equipment, Category II instrument landing systems, and so on, then the choice process is opened up. Malfunctions during flight also may require a search for an appropriate airport. The first step in the choice process is to generate a set of options that meet a minimum criterion, such as finding airports within fuel range. Usually weather conditions are considered next. Then the options are evaluated in terms of specific requirements, such as runway length, approach path, equipment available, familiarity to the crew, or maintenance capability. The actual strategies used by crews to select an alternate vary, but observations to date (Klein, 1993; Orasanu, 1990) suggest that they do not correspond to a full analytical procedure, such as a multi-attribute utility analysis (Edwards & Newman, 1982). A full analysis would involve evaluation of *each* option in terms of every variable relevant to the decision (e.g., weather, fuel consumption, runway length, airport facilities), and a mathematical formula would be used to combine all the information to yield the optimal choice. In fact, crews appear to make decisions in the most economical way, taking shortcuts in this process. They work toward a suitable decision in the shortest time, investing the least possible cognitive work. Options are often eliminated on the basis of one feature, such as weather, and are out of the running thereafter, unless no suitable alternate can be found and the process must be reopened. This pruning may leave only one acceptable option, which is chosen. (This is essentially an elimination by aspects strategy, Tversky, 1972.) However, if a few candidates are available, usually only two or three, one is chosen to match the constraints of the circumstances and the crew's preferences. Usually the most safety-critical constraint prevails; however, organizational policy also plays an important role here. The crew may try to choose an alternate that has a company maintenance facility or where replacement planes will be available for passengers to continue their flight. For example, in an ASRS report, a crew reported losing a tire during take off. Subsequently, the captain lost his heading information display and the first officer lost his attitude indicator. These problems were rectified after level-off and the crew decided to head for a company maintenance facility. However, as they climbed to flight level (FL) 180, cabin pressure went out of control, and they ultimately decided to return to their departure airport.

Decision difficulties arise when goals conflict or when no good choice is available. For example, the assigned or most desirable alternate might be satisfactory when the plane takes off, but the weather may deteriorate rapidly and may be below minimums by the time the flight arrives. The second-choice alternate may have clear weather, but it may be more distant, straining fuel resources. All options are evaluated in terms of their level of risk, but sometimes no low-risk option is available. Then risk must be played off against what will be gained in each case, factoring in the crew's level of confidence that they can follow through with the choice. In these cases, "what if?" reasoning may be needed. The crew needs to think about what might happen down the line. They are in a dynamic state: Their equipment may be changing over time (e.g., a fuel leak or a consequent system problem may develop with some probability), the weather is changing over time, and their location is changing over time.

Unfortunately, the scientific literature is quite barren with respect to guidance about how to make decisions under such circumstances. Obviously, many factors need to be taken into consideration, and the crew need to use all the knowledge and experience they possess collectively. Certain rules of thumb have been shown to be effective in time-pressured complex decision situations. These strategies may include elimination by aspects (described above, Tversky, 1972) or satisficing (Simon, 1955). Satisficing means stopping the search for an option as soon as the first acceptable option is found (rather than thoroughly evaluating all options to choose the best). Doing a full analysis of all options in a complex situation takes considerable time, which often is not available during flight.

2. *Resource management.* The second type of decision involving multiple options is the scheduling or resource management problem. These are situations in which several time-consuming tasks must be performed during a limited time frame. Tasks may include diagnosis of a system malfunction using checklists, radio communication with dispatch or ground controllers to evaluate alternates, and manual efforts, such as lowering gear or flaps. A decision has already been made that each of these individual tasks must be done. The issue is how to coordinate them, that is, how to accomplish them all so that their products are available when they are needed.

The cognitive work that must be done for this type of decision includes establishing priorities among the various tasks, assessing available resources, both equipment and human (in the cockpit and on the ground), estimating the amount of time available and the amount that will be consumed performing the various tasks, and developing a plan that integrates goals with resources, taking into account relevant constraints. This type of activity is considered decision-making because choices are made about what to do, who will do what tasks, and when they will be done. More properly, it should be called a complex of decisions that constitute a plan. Others call this a scheduling task (Moray, Dessouky, Kijowski, & Adapathya, 1991).

Perhaps most critical to this type of decision is priority setting. Certain actions must be accomplished within the time frame, such as extending the landing gear. Other tasks may be less critical. Diagnosing a problem may be desirable for safety reasons, but fixing the problem during flight may not be possible, so this task may be given lower priority. Plans need to be flexible. Certain actions may uncover other difficulties that require attention or may take longer than expected. Or air traffic delays may disturb the plan. Plan execution must be monitored for progress and revised as necessary to meet changing conditions. If it looks like everything will not be done in time (e.g., prior to landing), the captain may need to request vectors that will give him more time to complete tasks that must be done, or less critical tasks may be eliminated altogether.

Ill-defined Problems

The other two types of decisions hardly look like decisions at all. They consist of ill-defined problems that may or may not be clarified in the process of dealing with them. Ill-defined problems are ones resulting from ambiguous cues that make it impossible (initially) to say what the problem is that needs fixing. No match can be made to the condition side of a condition–action rule to trigger a response. Two strategies may be used to cope with this type of situation: manage the situation as though it is an emergency without clearly defining the problem, or diagnose and define the problem, and then work out a solution. The second type is more complex because no prescribed procedures exist for solving the problem. In addition, because of the ambiguity of the conditions, no single correct or best solution exists.

1. *Procedural management.* Certain cues leave the crew without a clear idea of the nature of the underlying problem. Various noises, thumps, vibrations, rumblings, pressure changes in ears, or control problems indicate that something has happened, but not necessarily what. Certain cues signal potentially dangerous conditions that trigger emergency responses, regardless of the source of the problem. Smoke, loss of pressure, an acrid smell, an explosion, or loss of control all signal "Land now." Little time is devoted to determining the source of the cues. All energies are devoted to finding an appropriate airport, running necessary checklists, getting landing clearance, declaring an emergency, dumping fuel, and landing. In a sense, these problems are treated as RPD situations, with the condition broadly labeled as "emergency landing" conditions.

The cognitive work done for this class of decision is primarily situation and risk assessment. Responses are clearly prescribed and highly procedural—once the situation is defined as an emergency. If the risk is judged to be high, then emergency procedures are undertaken. If the risk is not immediately defined as an emergency, then additional energy may be devoted to situation assessment.

Diagnosis of the cause underlying ambiguous cues can serve two purposes. It can clarify exactly what the problem is so that an appropriate specific action can be taken, and it can provide information that may be useful for fixing the problem. Particularly while in cruise, when workload is relatively low, the crew may devote time to diagnosing and fixing the problem. Risk assessment determines whether or not such efforts will be attempted, as diagnosis takes time and crew resources. But even if diagnosis does not lead to fixing the malfunction, it can turn the problem into one with a well-defined response (essentially a recognition-primed decision). Defining the problem clearly may lead to a more specific response than simply treating it as an emergency. For example, one crew reported to ASRS a high-frequency flutter through the airframe. A company mechanic on board visually inspected the craft and noticed that the right outboard aileron balance tab was loose. The crew consulted with flight control and company maintenance who recommended that they reduce their speed. When they did, the problem disappeared, and they were able to continue their flight without further difficulties. Had they not diagnosed the problem, they would probably have made an emergency landing, with its attendant cost and inconvenience for passengers.

Diagnosis does not always succeed (even with the help of ground maintenance), and the crew may have few choices other than to proceed to their destination without fixing the problem, or to make an emergency landing. For example, one crew reported that they had an anti-ice problem compounded by a pressurization problem. Cues were ambiguous as to the source of the problems. They divided the workload to try to figure out what was wrong, and when they couldn't diagnose the situation, they made an emergency descent. Another crew reported an unfamiliar rumbling and pressure in their ears that signaled a high rate of climb. Efforts at diagnosis were unsuccessful, so they too decided to land.

Subsequent maintenance discovered that the Electrical and Electronics compartment was not secured and the switch that should have signaled this problem was not working.

2. *Creative problem-solving.* Perhaps the most difficult types of decisions are embedded in complex situations that require creative problem-solving. Problem-solving means that in addition to defining the nature of the situation, response options must be generated that will lead to the goal. In other words, procedures do not exist to meet the needs of the situation. These cases tend to be extremely low frequency events; no one imagined such situations would arise, so no procedures were designed to cope with them. Perhaps the most extreme and celebrated case of a non-routine emergency was United Airlines flight 232 (NTSB, 1990), the DC-10 that lost all hydraulic systems at FL 330. An explosion in the number 2 engine caused debris to cut the hydraulic lines. The crew realized that they had no flight controls except engine power and then had to experiment to find any manner of controlling the plane in order to land it. Both situation assessment and response generation are required in such cases.

The cognitive work required by ill-defined problems is most varied of all the decision types. Diagnosis is critical. Often the problems that fall into this category are low-frequency events, which may mean that they are more difficult to diagnose. Diagnosis typically involves causal reasoning, which is reasoning backward from effects to cause. Hypothesis generation and testing are often involved. Depending on the nature of the problem, the range of tests that can be performed will vary. For example, in response to a power loss indication for one engine, the crew can manipulate the throttle to see its effect. If they find no effect, they may shut down the engine since it is not working. They may check to see if fuel is flowing to the engine. Tests are often embedded in checklists.

Even after the nature of the problem has been determined, no ready solutions are prescribed. In the case of UAL 232, the captain spent considerable energy on situation assessment, determining what capability he had left after the hydraulic failure (Predmore, 1991). The two outboard engines were still running, but no flight controls were operative. His goal was to control the direction and level of flight. Knowing that the only control he had was engine thrust, he and his crew determined that they could use asymmetrical engine thrust to turn the plane. The power level controlled altitude. Continuous monitoring was required to adjust the power to keep the plane from rolling over on its back and to control oscillation.

While the case of UAL 232 is extreme, ASRS reports indicate that crews do, in fact, encounter situations that are not covered by the Federal Aviation Regulations, minimum equipment lists, or checklists. In these cases crews must use their ingenuity, experience, and creativity to deal with the problem. For example, a captain of a large transport on a cross-country flight reported a low level of oxygen in the crew emergency tanks while at FL310. No guidance concerning how to proceed was available in company manuals. The cause of oxygen depletion could not be determined in flight, nor could the problem be fixed. Regulations require emergency oxygen in case of rapid decompression, so the crew came up with a creative solution. They descended to FL250 and borrowed the flight attendants' walk-around oxygen bottles. (Different O_2 requirements are specified for flight attendants above and below FL250.) This solution allowed them to continue to their destination rather than to divert to a base that had O_2 bottles for the cockpit system or to descend to 10,000 feet, eliminating the need for the O_2. The latter option would have meant that the flight would not have had sufficient fuel to reach their destination because of rerouting around bad weather.

This example is interesting because it illustrates consideration of multiple options, creation of a novel solution, sensitivity to constraints, and explicit risk assessment. In creating his solution, the captain was aware that he would not be able to communicate with ATC in an emergency if he was using the walk-around O_2 bottle, as it has no microphone. But he judged the likelihood of a rapid decompression to be sufficiently low that he chose this option. Another constraint was fuel: the captain wanted to conserve fuel because of bad weather at his destination. He was concerned about the possibility of a missed approach or further diversion. An early decision to divert would have been the most conservative decision, but it would not have met the goal of getting the passengers to their destination in a timely manner. This example also indicates that there is no right or wrong solution; there is only a solution that works given the conditions that exist.

This effort at classifying decisions in terms of situational demands is a first step toward understanding what makes certain kinds of decisions difficult and where the weak links are. The six types of decision fall on a continuum ranging from simple to complex, requiring little cognitive work to considerable effort. One reason for laying out these differences is to create an appreciation for the fact that no single unified method for improving decision-making will work. A number of heuristics have some general power, but the specific requirements of each type of decision problem differ considerably. This issue is addressed in the final section on training.

HOW DO WE RECOGNIZE A GOOD DECISION IN THE COCKPIT?

Criteria for judging the quality of decisions in the cockpit are not necessarily the same as those for judging decisions in the laboratory. Decisions in the laboratory are judged on the basis of logical consistency and optimality, two highly valuable criteria. However, reaching an optimal decision is cognitively demanding and time-consuming. It means using all available information, which may exceed the mental capacity of the unaided human decision-maker (Simon, 1955). Decisions in the laboratory can be evaluated against abstract criteria because the problems are solved outside of any meaningful context and nothing hinges on the outcome. The goal of laboratory tasks is to make a decision. However, the goal in the cockpit is to fly the plane safely from point A to point B in accord with regulations and company policy, while satisfying passengers' comfort and convenience needs. Decisions are embedded in and support that primary task.[1] Crews are judged on how well they perform their task, and decisions should be evaluated in terms of their contributions to overall task performance: safety, efficiency, effectiveness. Effectiveness includes satisfying multiple goals such as company policy and customer comfort and convenience; efficiency includes fuel economy and timeliness.

Unfortunately, at present no theory relates decision quality to overall task performance. In principle, we expect that a series of good decisions will lead to a highly successful flight (i.e., safe, effective, efficient). All we know with confidence is that bad decisions contribute to accidents (Diehl, 1991; the Chapter by Kayten). We have no evidence that improving the quality of decisions from "good enough" to optimal would buy more safety, efficiency, or effectiveness.[2] Christensen-Szalanski (1986, 1993) examined the quality of medical decisions and the quality of resulting diagnosis and treatment and found only a loose relationship. Because diagnoses and treatments are categorical, slight improvements in the quality of a decision had little effect on outcomes. The only case in which decision improvements affected performance was when they pushed a decision over a threshold that distinguished treatment A from treatment B.

Clearly, we want crews to make the best decisions they possibly can make, but they must operate with the resources available to them—specifically, time, mental capacity, and information. Performing a full analysis to evaluate all options (e.g., using a multi-attribute utility analysis, Edwards & Newman, 1982) costs a lot in time and mental resources (Payne, Bettman, & Johnson, 1988; Tolcott, 1991). Normative decision models ignore this practical reality, but crews cannot afford to. Costs are associated with generating all options, gathering all relevant information, evaluating the options in light of relevant attributes, and integrating the data to yield the optimal decision. These costs are measured in crew time and workload. A decision strategy that is "good enough," though not optimal, and is low in cost may be more desirable than a very costly, and perhaps only marginally better, decision. In addition, the appropriateness of applying normative models to decision-making in dynamic, time-pressured, action-oriented situations has been questioned (Brehmer, 1991). Given the inap-

[1]For a discussion of the differences between decision-making in the laboratory and in naturalistic environments, see Orasanu and Connolly (1993).

[2]One exception may be the case of flight replanning, in which an optimal flight plan can be selected to provide maximum fuel economy, smoothest flight (avoiding weather), or fastest arrival. Computer devices are required to assist such efforts, however (see Smith, McCoy, Layton, & Bihari, 1992).

propriateness of normative criteria, process criteria might be considered instead. That is, decision quality may be judged by asking how the decision was made. Actually, two questions are embedded in this one. The first concerns how decisions are made in dynamic natural environments. The second concerns how crews collaborate in making decisions (as opposed to individuals). I return to these questions in the next section.

A sizable literature shows unaided human decision-making in formal laboratory tasks to be nonoptimal and to violate logical principles, compared to normative standards (Kahneman, Slovic, & Tversky, 1982). Instead, people tend to use heuristic strategies, or mental shortcuts. Optimality requires that all available information be factored into the decision, but heuristics ignores some information. Options are pared down and the problem is simplified to reduce the information-processing load. Heuristic strategies yield adequate but not optimal decisions. In Simon's (1955) term, people often "satisfice," settling for the first choice found to be acceptable. Many people concerned with decision-making want to stamp out heuristics as defective forms of reasoning. Yet there is little evidence that they are bad under some everyday reasoning circumstances. To the contrary—under time pressure certain heuristic strategies have been found to yield better outcomes than truncated (and therefore incomplete) full analysis of options (Payne et al., 1988).

Research grounded in normative decision models tends to ignore the enormous power conferred by domain expertise. Research on expertise has focused mainly on problem-solving rather than on decision-making per se. However, the findings are relevant to the broad set of cockpit decisions described in this chapter (Johnson, 1988). Experts differ from novices mainly in the structure and richness of their knowledge bases. They have more complete and accurate "mental models" for the domain which allow them to interpret cues and to predict what will happen in the future (Johnson-Laird, 1983; Rouse & Morris, 1986). Expertise may be expected to contribute to cockpit decision-making in three ways (Chi, Glaser & Farr, 1988). First, expert knowledge facilitates rapid and accurate perception and interpretation of problems. Experts can "see" problems in terms of their underlying structure, which enables them to frame appropriate solutions. They can size up situations quickly. This type of knowledge is needed to recognize the conditions that trigger go/no-go or RPD decisions. Experts' mental models of aircraft systems also contribute to diagnostic situation assessment, used to clarify ambiguous problems (Cannon-Bowers, Salas, & Converse, 1991). Second, experts have more specific knowledge in their memory storehouses. This knowledge should include stored condition–action patterns corresponding to go/no-go and RPD decisions. These patterns are similar to the thousands of patterns chess masters have in memory (Chase & Simon, 1973). Experts should have to do little work to retrieve these stored condition–action rules. Third, expert knowledge provides a basis for risk assessment. Because of their experience with aircraft systems and routes over many hundreds or thousands of flight hours, expert pilots

can assess the likelihood of various kinds of problems occurring. They can infer likely causes and project what is likely to happen in the future, given no action or as a consequence of actions they might take. Finally, experts have more problem "cases" or stories in memory, based on their own experience or professional lore, that guide their search for information or suggest solutions.

It should be pointed out that knowledge is not a shield against errors. Actually, expert knowledge is the foundation for heuristics, which sometimes result in poor judgments. (For a thorough treatment of the role of knowledge in heuristics and biases, see Cohen, 1993a, 1993b). That same knowledge is responsible for efficient functioning most of the time, but occasionally it leads one astray. For example, Maher (1991) reports on a flight destined for Lexington, Kentucky, that actually landed at Frankfort, Kentucky. He attributed this error to the heuristics of availability and representativeness and suggested that training should try to eliminate their influence. However, it makes little sense to try to get people not to use their knowledge. Instead, it might be more productive to help people avoid traps by using other kinds of strategies, such as checking, monitoring, and verifying ambiguous information.

Two other points about expertise: First, expert knowledge only confers an advantage on problems that are meaningful within the expert's domain. For example, chess masters show remarkable memory for the location of chess pieces that represent positions during play (Chase & Simon, 1973). But if those same pieces are placed randomly on the chessboard, the masters' recall is no better than that of novices. The message is clear for decision-making in the cockpit: expertise may reach its limits on problems that are so low in frequency that they are unfamiliar to the crew, and new systems that violate long-term pilots' mental models may interfere with effective decision-making involving malfunctions in those systems. Evidence supporting these predictions is found in McKinney (1992), who reported that expertise conferred no advantage to Air Force pilots making decisions about unique system malfunctions; it did lead to better decisions in more routine cases. A second implication from the expertise literature is that pilots who are relative novices to the plane, company, or routes will probably not be as efficient or effective as more experienced pilots in assessing situations, making quick condition–action decisions, predicting future events, or selecting decision-relevant information. Vast amounts of experience are necessary to get to the point.

HOW DOES CREW DECISION-MAKING DIFFER FROM INDIVIDUAL DECISION-MAKING?

So far the discussion has been about decision-making in the cockpit, without specific reference to who is making the decision. Cockpit decision-making is defined as a team task, yet it is the captain who has ultimate responsibility for decisions that are made. The crew provides input from a variety of information sources: personal experience, aircraft systems, weather, air traffic control (ATC), and dispatch. The presence of multiple eyes, ears, heads, and hands would lead one to expect crews to make better decisions than individuals. Additional cognitive resources can monitor changing conditions more carefully, back each other up, assess the situation, provide alternate perspectives, reduce workload, generate options, suggest strategies, and identify obstacles. Yet research on group problem-solving and decision-making indicates that groups often do worse than individuals solving the same problems (Orasanu & Salas, 1993). Individuals do as well as groups on tasks for which there is a right or best answer, or those for which an effective strategy will lead to a good answer. However, teams do better in situations like the cockpit, where the solution depends on contributions from multiple sources and where coordination is required (Mullen & Goethals, 1987).

Even when the task is one that depends on team effort, there are many ways in which a team can perform in a less than ideal manner. Factors that detract from team efforts are either process failures or performance failures. *Process failures* (Steiner, 1972) are those stemming from the team's interpersonal processes: the intellectual and communicative processes by which members pool and assemble their resources, allocate responsibilities, and evaluate each other's contributions. A number of process failures stem from failure to question assumptions: Crew members assume they know each others' goals, or one person thinks he or she is the only one who sees the situation differently from others. A second process failure is based on shared misconceptions: Shared experience leads the crew to see a situation similarly, but incorrectly, and they have greater confidence in that wrong view because of their numbers. Third, a lack of cohesion may interfere with a crew's performance: Interpersonal conflict may lead to a refusal to cooperate. In a related vein is "social loafing": A crew member may abdicate responsibility because he or she thinks someone else will take care of the problem. Finally, some research suggests that groups make riskier decisions than individuals, perhaps because of dilution of responsibility, but this depends on the nature of the tasks (Davis & Stasson, 1988). Unfortunately, little experimental research exists on decision-making by teams of professionals like cockpit crews, so many of the findings reported here are based on work with ad hoc groups of college students performing laboratory tasks (Druckman & Bjork, 1991).

Performance failures are due to problems in accomplishing the task rather than to interpersonal process factors. These include interruptions from other tasks (e.g., ATC calls that must be answered); failure to communicate critical information in a timely manner (e.g., reporting on actions taken or sharing of information obtained); failure to complete critical tasks in time, usually due to poor task prioritization (e.g., computing landing weight or fuel consumption); and ambiguous goals or task assignments (not enough information is provided by the captain to enable each crew member to carry out the assigned task) (Leedom, 1991).

A third factor that pertains to individuals rather than the crew as a whole, but that is important in determining the decisions that may be made in critical circumstances, is *hazardous attitudes* (Diehl, 1991; FAA, 1991). These include: *antiauthority* (Don't tell me what to do), *impulsivity* (I must do something now), *macho* (I can do anything), *invulnerability* (Nothing will happen to me), and *resignation* (What's the use of trying?). Diehl (1991) has prescribed antidotes for each of these and reports reductions in accident rates as a result of training to overcome these attitudes in military and general aviation environments.

All three factors can contribute to poor decisions because they interfere with doing the work needed to make a good decision. In addition, hazardous attitudes may increase the amount of risk that crews will accept. The critical question remaining, however, is what features contribute to *effective* crew decision-making? This question is addressed in the next section.

WHAT CONTRIBUTES TO EFFECTIVE CREW DECISION-MAKING?

Given that the issue of defining good cockpit decisions was bypassed in an earlier section, the question of what contributes to effective crew decision-making may seem somewhat strange. The earlier discussion concluded with the suggestion that decision-making may be evaluated in terms of its contribution to overall *task performance*, that is, safety, effectiveness, and efficiency. Furthermore, attention should be paid to the *process* by which a crew reaches its decisions. Considerable data exist on crew performance in high-fidelity full-mission simulations (e.g., Oser, McCallum, Salas, & Morgan, 1989), and several studies have examined decision-making in those contexts. Relations have been identified between features of crew processes and overall levels of crew performance (Kanki, Lozito, & Foushee, 1989; Murphy & Awe, 1985; Orasanu & Fischer, 1991; Stout, Cannon-Bowers, Salas, & Morgan, 1990). While these findings are all correlational, they at least provide a basis for describing decision-relevant behaviors characteristic of crews that perform more or less effectively in simulated flight. Causal models have not yet been validated.

Four aspects of crew behavior that support cockpit decision-making have been identified (Orasanu, 1990). They are associated with effective crew performance, where performance is judged by operational errors (mainly violations of standard procedures and aircraft control problems such as altitude deviations). These features pertain to the crew as a whole, rather than to individual crew members. Effective crews are characterized by the following features, which will be described in some detail: good situation awareness, high levels of metacognition, shared mental models based on explicit communication, and efficient resource management.

Situation Awareness

Situation awareness involves interpreting situational cues to recognize that a problem exists which may require a decision or action. Crews must go beyond merely noticing the presence of cues; they must appreciate their significance. Doing so successfully depends on knowledge and experience in similar situations. For example, recorded weather information at airports is available to all pilots. Hearing that there is less than a 5° spread between temperature and dew point means that fog is likely, although there may be no mention of fog in the report. An alert pilot will recognize this potential problem for landing and seek further information.

Recognizing and defining the nature of a problem encountered in a dynamic environment such as flying is the first and perhaps most critical step in making an effective and safe decision. The significance of situation awareness is clear in Freeman & Simmon's (1991) analysis of 244 in-flight incidents reported to a major carrier. Of that entire set of incidents, 143 of them (or 59%) were classified either as problems in perceiving that a problem existed ($n = 81$) or in recognizing the significance of the cues for the safety of the flight ($n = 62$). If a crew does not realize they have a problem, they surely are not going to begin trying to solve it. Unfortunately, problems have a way of evolving, and by the time less sensitive crews are aware that a problem exists, the situation may be much more risky.

Sometimes cues are subtle and do not signify a problem at the moment, but forewarn that conditions may deteriorate in the future. For example, turbulence en route may remind a crew that a weather front is moving in to their destination. They may begin to consider the possibility of a missed approach or diversion if weather drops below minimums. Situation awareness allows crews to plan ahead and prepare for contingencies, which is an element under the next component.

Metacognition

Metacognition is a word from the research world that means, literally, thinking about thinking. It refers to reflection on and regulation of one's own thinking (Brown, Armbruster, & Baker, 1986; Flavell, 1981; Garner, 1987). In the cockpit, where thinking is a collective activity, metacognition involves defining the problem and working out a plan to solve it, determining that a decision must be made, and deciding what information and resources are needed and what are available. As used here, metacognition refers broadly to a reflective executive function, as opposed to a narrower definition sometimes adopted in the decision literature which focuses on degree of confidence in one's judgments (Evans, 1989).

A metacognitive framework was used by Orasanu (1990) to analyze crews that differed in their overall performance in a full-mission simulated flight at NASA–Ames Research Center (Foushee, Lauber, Baetge, & Acomb, 1986). Analysis of crew communication showed that higher and lower performing crews differed in their levels of metacognitive activities when faced with in-flight abnormalities. All crews (flying a simulated B-737) encountered turbulence en route to their destination. (See Figure 5.2 for a schematic of the scenario.) High cross-winds made the landing illegal, so a missed approach was required. During climb-out one of the hydraulic systems failed, which increased workload and complicated the choice of an alternate. The hydraulic failure meant that braking power would be reduced, and gear and flaps would need to be lowered manually. Because the gear could not be retracted once lowered, a second go-around was not desirable. None of these problems in itself was difficult, but their confluence increased the workload substantially and seemed to increase the difficulty of both the choice decision (the alternate landing site) and the scheduling decision (task prioritization and resource management) for some of the crews.

More effective crews paid attention early on to the turbulence and to the possibility of a missed approach. They reviewed the approach plates, checked to see whether Category II instrument landing equipment was available and working, and considered possible alternates. They also checked weather frequently and realized the cross-wind problem before going down to decision height. Following the missed approach and hydraulic failure, more effective crews all adopted a conservative strategy: They requested a holding pattern to buy time while they collected information about weather at possible alternates, checked on runway lengths and approaches, and calculated fuel availability. When low-error crews made their choice of an alternate, they used more safety-relevant information. All these behaviors can be considered evidence of metacognition. The crews reflected on what they were trying to do, how they could do it, what additional information they needed, and what the likely results might be.

Several recent studies of cockpit crews support Orasanu's (1990) conclusions concerning the role of metacognitive processes in effective crew performance. The importance of planning to overall mission effectiveness was demonstrated by Pepitone, King, & Murphy (1988), who found fewer operational errors among crews that made more contingency plans. Also supporting the importance of a broad plan was the Smith, McCoy, Layton, & Bihari (1992) finding that more effective crews emphasized strategies that kept open more options in a flight replanning problem. A second metacognitive factor is sensitivity to information needed to solve a problem. Cohen (1992) found that more experienced captains faced with a flight replanning task paid more attention to recommendations from dispatchers than did less experienced captains. While this finding might be explained on the basis of the senior captains' greater organizational integration, it could also reflect their greater appreciation of the value of this source of information. Dispatchers have a broad view of the entire system, both weather and traffic, and can provide more optimal suggestions.

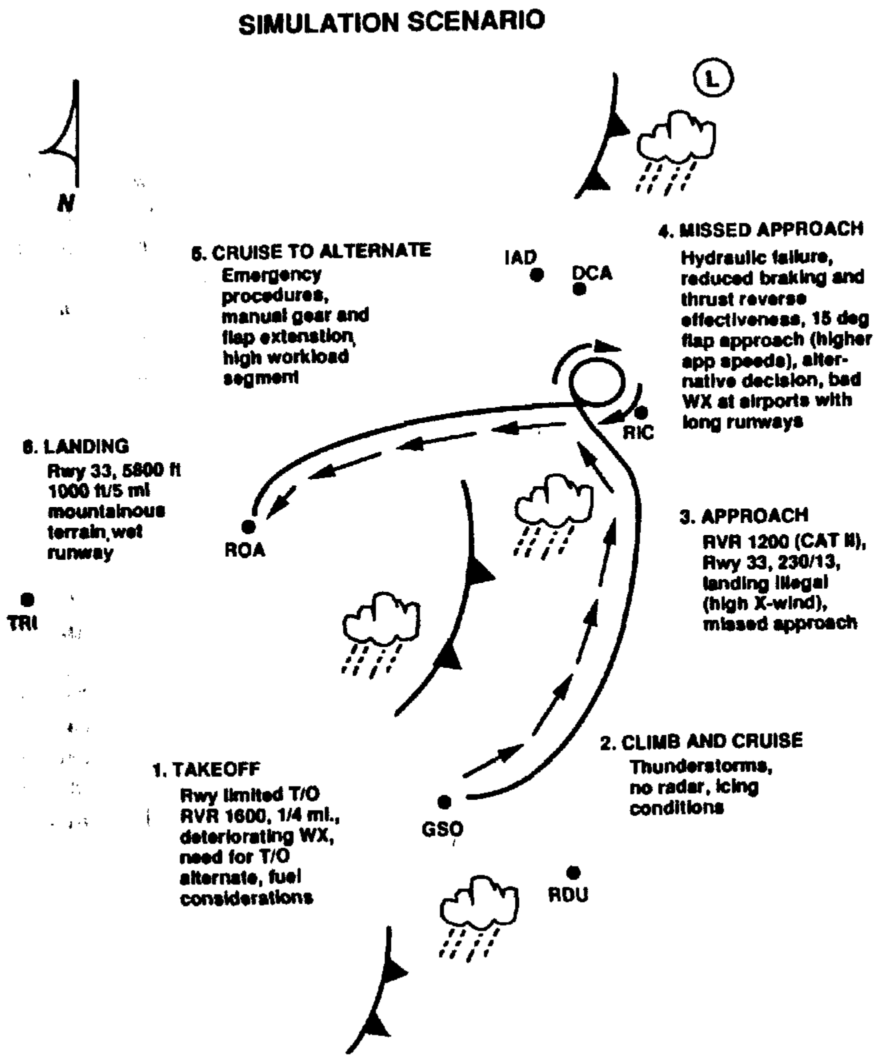

Figure 5.2 Overview of the simulation scenario. WX, weather; X-wind, cross-wind. (Originally from Foushee, Lauber, Baetge, & Acomb, 1986.)

Shared Mental Models

When a crew encounters a problem in flight, two kinds of shared knowledge may contribute to effective solution: shared background knowledge and shared problem models. Shared background knowledge refers to the knowledge the crews bring with them to the cockpit based on common training and experi-

ence: knowledge of aircraft systems, standard procedures, regulations, company policy, and crewmember roles and responsibilities (chapters by Ginnett and Hackman; Cannon-Bowers et al., 1990). This kind of shared knowledge allows the crew to function efficiently in routine situations because it allows them to anticipate events and each others' actions. Hutchins & Klausen (1991) have shown how shared knowledge allows one crew member to interpret ambiguous gestures, facial expressions, and utterances of the other crew member while making a change in heading. When a flight is uneventful, little communication is required beyond the standard monitoring, callouts, and sharing of weather and clearance information obtained over the radio to assure crew coordination. All crew members play their assigned roles in synchrony, like a string quartet (cf. Hackman, 1987).

However, when a problem arises, especially one that is ambiguous and cannot be solved "by the book," or when multiple problems co-occur, then the crew needs to get organized. Communication is needed to assure that each crew member understands basic information about the situation: what the problem is, what the plan is for solving it, who does what. In this case, the crew needs to create a shared problem model. This model uses shared background knowledge but is specific to the immediate problem and its solution. A shared problem model is necessary to assure that all crew members are solving the same problem and have the same understanding of priorities, urgency, cue significance, what to watch out for, who does what, and when to perform certain activities.

Note that each participant can have his or her own understanding of the situation and plan for coping with it. The captain can give commands and the crew members can carry out their jobs. But without shared understanding of the overall goal, there is no guarantee that all crew members will be working toward the same ends. Obviously, the degree of communication required depends on how familiar the problem is to the crew and how complex it is. The greatest amount of communication is required in ill-defined or non-routine problems. For routine problems, crews may show implicit coordination and little overt discussion of what to do (Kleinman & Serfaty, 1989).

Shared problem models are created through communication—all crew members may contribute to them, depending on who has relevant information. Certain types of utterances contribute specifically to building shared problem models and working out solutions. These utterances are distinct from standard cockpit talk required to fly the plane, namely, call-outs, check lists, system monitoring, ground communication, and associated acknowledgements and replies, but are clearly built on these. This distinct type of talk enables the crew to get organized when a problem is encountered.

Model-building utterances perform the following functions: recognize and define the problem, state goals, state or suggest plans or strategies, offer explanations, and predict outcomes. Other utterances are more action-oriented but still augment the problem model by making explicit what is to be done and who is to do it. These include specific task assignments and commands. Orasanu & Fischer (1991, 1992) analyzed the performance of 2-member (B-737) and 3-member (B-727) crews in full mission simulations at NASA–Ames Research Center. Both simulations used the same complex scenario described earlier (weather-induced missed approach followed by a hydraulic system failure). (For full descriptions of the original studies, see Chidester, Kanki, Foushee, Dickinson, & Bowles, 1990, and Foushee et al., 1986).

The Orasanu & Fischer (1992) analysis showed that crews talked more overall during the abnormal phase than in the normal phase of the flight, as would be expected. However, the increase in their talk was concentrated in certain categories. Both captains and first officers stated more goals and plans/strategies during the abnormal phase and made more explicit task assignments. These data support the notion that crews in fact respond to the exigencies of the situation and organize themselves to cope. Moreover, Orasanu & Fischer (1992) found that captains of higher performing crews (those who made fewer procedural or aircraft handling errors) were more explicit in their problem-related talk than were captains of lower performing crews. They stated more plans or strategies and made more explicit task assignments. This study showed that the captains set the tone and contributed disproportionately to creating the shared model. They created the context that allowed other crewmembers to participate. This pattern is confirmed by an analysis by Murphy & Awe (1985), who found that the quality of decision-making in 16 air transport crews (in simulated flight) was a function of the decision efficiency and the quality of the captain's communication. The decision efficiency measure reflected the degree to which the problem was clearly defined and relevant information was obtained. In turn, decision efficiency was predicted by quality of decision communication, command reversal, and crew coordination. Command reversal refers to the first officer taking over the captain's usual duties; it was negatively related to decision efficiency, meaning that when the captain was clearly in command, decision-making was more efficient.[3]

What these findings suggest is that shared problem models serve as organizing frameworks within which crews solve problems and make decisions. By articulating goals, plans, and strategies, effective captains create a context for interpreting their commands, observations, and information requests. The shared model enables other crewmembers to make suggestions, to offer information useful for solving the problem, and to coordinate their actions. Good crews also use resources outside the cockpit, such as ground controllers and company dispatchers, who can provide assistance.

[3]This finding should not be taken to mean that first officers should not take responsibility for managing a situation in the cockpit if conditions warrant it. Sometimes command reversal is the best way for a crew to manage a situation.

Resource Management

Resource management is itself a type of decision-making, but it also bears on the quality of other decisions that must be made during the critical time period. Crews that manage their resources well reduce the demands on their own cognitive resources, especially during high-workload phases of flight, freeing them to deal with other complex decision requirements. Resource management involves the management of information, cognitive work, communication, and actions that must be accomplished within a fixed time or event window. Effective resource management requires an understanding of what must be done, what resources are available, the time required to carry out various tasks, and the cognitive and non-cognitive demands of various events. In addition and most important, the captain must clearly understand the relative priorities associated with each task and use this information to schedule tasks and assign crewmembers responsibility for accomplishing them. Well-managed crews look as if they are guided by an overall plan that matches resources to goals, and everything fits in. All tasks are accomplished in a well-coordinated manner. Poorly managed crews are constantly playing catch-up and appear poorly coordinated. Often important tasks do not get done.

What accounts for these differences between more and less well managed crews? First, it appears that captains with good metacognitive skills have a better overall picture of their strengths and weaknesses and potential problems. Armed with this information, they develop overall time and resource management strategies designed to give themselves clear thinking time and flexibility. They either use low-workload periods to do contingency planning, or explicitly structure tasks to give themselves time to work on problems. Strikingly different overall strategies appear to be optimal depending on crew size, and thus the total cognitive resources available (Orasanu, 1990; Orasanu & Fischer, 1992). In two-member (B-737) crews, more effective captains used low-workload periods to prepare for possible high-workload periods. Specifically, with bad weather at their destination, they reviewed approach plates early and often, included missed approach guidance, and considered the possibility of needing an alternate. When workload became intense, these captains talked very little. They stated their goals and plans and assigned the first officer to work on the system malfunction, while they (the captains) flew the plane. Those captains gave few commands during the high-workload period. Instead, they spelled out overall priorities and sequences for completing various tasks. They created a shared problem model within which the first officer could work out details of how to get the tasks done. In contrast, captains in lower performing crews gave many commands during the high-workload phase but provided no overall plan or strategy for getting the work done. Coordination of these crews was very disjointed; first officers seemed to have trouble completing one task before they were called on to do another.

In three-member crews, a very different resource management strategy was associated with effective crew performance. More effective captains assigned flying the plane to the first officer while they, the captains, worked on the system malfunction problem and decision about an alternate with the second officer. These captains' rate of talk, including goals, plans, commands, and explicit task assignment, went up significantly during the abnormal or high-workload phase. Less effective captains of three-member crews flew the plane themselves and assigned the task of working out the problems to the first and second officers. But those captains still tried to manage the problem-solving activities. It appears that managing problem-solving and complex decision-making while flying a plane is difficult to do. So we see very different patterns associated with effective performance depending on the crew resources available.

Further support for the importance of good resource management to overall flight performance comes from research by Wickens & Raby (1991), who examined performance of single pilots flying low-fidelity simulators. They found that high performers (defined by low frequency of errors such as altitude deviations) carried out critical tasks (e.g., landing gear and flaps) earlier than low performers and scheduled other "must do" tasks at more optimal times. Clearly, the better performers showed greater sensitivity to timing and better planning. Presumably, their effective task management contributed to their high performance.

Unfortunately, life sometimes presents challenges for which no specific training or planning can prepare one. Such a case was the loss of all hydraulic systems at 33,000 feet in United Airlines flight 232 (NTSB, 1990), referred to earlier. The captain's management of that crew and the level of crew coordination (including ground personnel) contributed to saving lives that surely would have been lost otherwise. Predmore (1991) analyzed the tapes of the last 32 minutes of that flight. His analysis showed that during the high-workload period after the failure, the captain used his crew resources in an efficient manner. A check airman happened to be a passenger on the flight and was recruited to assist in situation assessment by visually inspecting the nature of the damage. Then he was used to manipulate the throttles (once the crew discovered they could control the plane somewhat using that mechanism). That left the captain free to manage the situation, which he did with the aid of ground controllers and the company dispatcher. Through composure, good crew coordination and communication, and a heavy dose of luck, that plane was brought to earth, though not without some loss of life.

How do the four components I have described contribute to decision-making? Situation assessment is necessary for recognizing that a decision must be made or an action must be taken. Metacognition is involved in determining an overall plan and the information needed to make the decision. Shared situation models are needed to exploit the cognitive capabilities of the entire crew. Shared models also assure that all participants are solving the same problem. And resource management assures that time, information, and mental resources will be available when they are needed.

CAN WE TRAIN CREWS TO MAKE BETTER DECISIONS?

If we want to improve performance by cockpit crews, should we focus training efforts on helping them to be more rational decision-makers? Or should we train them to interpret cues, be metacognitive, make plans, build shared problem models, and manage their resources? Recent research findings suggest that the latter might be more productive. Evidence is accumulating on the lack of success of "debiasing" efforts (Fischhoff, 1982) and efforts to improve statistical reasoning (Cheng, Holyoak, Nisbett, & Oliver, 1986).[4] On the other hand, positive evidence is accruing on training in perceptual skills needed for situation assessment (Getty, Pickett, D'Orsi, & Swets, 1988), on metacognitive skills (Nickerson, Perkins, & Smith, 1985), and on crew resource management skills (Chidester, 1987; Helmreich, 1987; Helmreich, Chidester, Foushee, Gregorich, & Wilhelm, 1989; Helmreich & Wilhelm, 1991).

At this point in research history, no basis exists for believing that it is possible to develop training techniques to improve all-purpose decision-making skills. The problem is that different component skills are involved in the six types of decisions described earlier in this chapter. Efforts at training general-purpose cognitive skills have notoriously met with failure (Bransford, Arbitman-Smith, Stein, & Vye, 1985; Sternberg, 1985, 1986). Conclusions from a large body of research show that cognitive skills are specific to the domain in which they are to be practiced. Strategies are learned most effectively in conjunction with the domain-specific content (Glaser & Bassok, 1989).

Consider the six decision types discussed earlier. The cognitive work required by each type demands different types of training. Following is a sketch of what organizations might want to teach for each type of decision.

1. *Go/no-go decisions.* Since these decisions usually must be made under severe time pressure and involve considerable risk, the amount of thinking should be minimal. Essentially, crews must be taught to recognize the sets of conditions that trigger the response, Stop what you are doing! (usually taking off or landing). The other necessary element is risk assessment, especially when conditions are borderline. Training should focus on developing perceptual patterns in memory that

[4] "Debiasing" efforts attempt to help people use all available information which they might otherwise ignore, resulting in biased judgments. For example, people tend to give little weight to the base rate frequency of certain outcomes or events (e.g., the rate at which certain systems fail in the cockpit) (Kahneman & Tversky, 1982).

constitute the conditions for aborting an action. Such training should be conducted under realistic time pressure and should include cases that are borderline or have additional contingencies that require more complex risk assessment.

2. *Recognition-primed decisions.* As with go/no-go decisions, crews must be trained to recognize situational patterns that serve as input to condition–action rules. But in this case they must also learn the response side of the rule and its link to the condition. For example, if a rapid depressurization occurs, the crew must know to descend immediately to a lower altitude. Evaluation skills also must be trained: The crew must ask, What will happen if I take this action? What will happen if we do not take this action? Is there a reason not to take this action?

3. *Response selection decisions.* When a single option must be selected from a set, crews must recognize multiple options and evaluate them in terms of how well they satisfy the goals and meet constraints. Often they must consider trade-offs among competing goals which are satisfied by different options. A traditional decision-analytic approach would be to train crews to perform a multi-attribute utility analysis. However, this is a very costly procedure in terms of time and resources. A more efficient approach might be to train crews to use "satisficing" (Simon, 1955) or other heuristic strategy that yields a satisfactory, though not optimal, solution. Two heuristic strategies that may be appropriate in certain environments are elimination-by-aspects (Tversky, 1972) or dominance-structuring (Montgomery, 1989, 1993). In the former, options are eliminated if they fail on one criterion (e.g., weather or runway length) and are not evaluated on other criteria. In the ideal situation, only one acceptable option remains. Dominance-structuring proceeds in the opposite direction. Evidence supporting various options is reevaluated to support a single choice.

4. *Resource management decisions.* The relative priorities of various tasks, especially critical ones, must be part of the basic knowledge of all crewmembers. Skills that enter into this type of decision include estimation of the time required to complete various tasks, knowledge about the interdependencies among tasks, and scheduling strategies. An important strategy for captains appears to be structuring activities to free up time for thinking. When problems are ambiguous, requiring diagnosis or creative problem-solving, captains may manage best by off-loading some of their own tasks, like flying the plane, to other crew members.

5. *Non-diagnostic procedural decisions.* This is the least clearly defined type of decision. It involves a cue pattern that falls into a category with no prescribed response. The nature of the problem is unclear. Many different types of ambiguous cues (e.g., loud noise from air rushing in the cockpit, strange vibrations, smells) may signal dangerous conditions. The prescribed response for many of these cases would be to land as soon as possible (essentially a procedural solution). This type of decision may be a variant of the RPD category, but with a non-specific condition side. Training for these cases would involve mainly situation assessment and risk assessment. Cues that signal possible emergencies need to be distinguished from those that are troublesome but not severe enough to precipitate an emergency landing. Knowledge of the specific aircraft type and its systems would be most useful in this case.

6. *Problem-solving.* These tasks are the most complex, because they involve both diagnosis to determine the nature of the situation and response generation. Once the nature of the problem has been determined, there are no recommended solutions "in the book." Crews must determine what their goals are, develop a plan and candidate strategies, and evaluate the strategies and planned actions based on projections of outcomes. General reasoning strategies such as means–ends analysis may be appropriate for very unfamiliar problems. Alternatively, the crew may try to think of similar or related cases in their own experience or in aviation lore. Case-based reasoning using analogies can offer suggestions for proceeding when little specific knowledge is available (Kolodner, 1987). Solutions that worked in the past are evaluated by imagining their consequences in the present situation. Training for case-based reasoning involves presenting many examples of other people's experiences, as is currently done in many CRM courses. Videotaped reenactments of in-flight emergencies are used to illustrate how those crews coped with the problem. "Hangar flying" provides an informal means for crews to share experiences that may help each other cope with unexpected events.

The above recommendations are based on the structure of the specific types of decision presented by the environment. Different situations demand different kinds of strategies. However, training suggestions also derive from the analysis of factors contributing to effective crew performance. These suggestions cut across all types of problems but may be more significant for one type than others.

The first step in all decisions is *situation assessment.* Both rapid pattern recognition and diagnostic skills are needed. Crew recognition of danger cues should be automatic. Crews also need training to pay attention to ambiguous or worrisome cues. Diagnostic skills may be needed to figure out what the situation is before a decision can be attempted. For example, split flap and asymmetrical flap configurations impose different landing requirements in a B-727. Considerable diagnostic effort may be required to distinguish between them. This is an example of a rare occurrence but one that crews must master.

A second general skill that is a component of all decisions is *risk assessment.* Often safety is pitted against other goals such as saving fuel or getting the passengers to their destinations on time. Organizational policy plays a critical role in these trade-offs and should be explicitly acknowledged when goals may conflict. Organizations and crews must recognize that some level of risk always exists and that there are always trade-offs. Both explicit policy guidance from the organization and reinforced practice by the crew are needed so that crews will be able to achieve solutions that optimize safety and other goals. Training should also emphasize using ground support (dispatch and ATC) to get a bigger picture of the crew's situation in order to minimize risk.

Perhaps the most trainable decision-related skill complex is *metacognition* (see Means, 1993). Abundant research exists supporting the trainability of these skills across wide ranges of populations (Brown et al., 1986; Garner, 1987). A study supported by the Department of Defense to improve decision-making by senior executives found that metacognitive skills were most affected by training (Laskey, Leddo, & Bresnick, 1989). However, learners must have a repertoire of relevant strategies: what they learn is how best to use them. Metacognitive training involves problem analysis (the demands of the problem, information needs, and resources available), strategy development, and the conditions under which various strategies can best be used. The goal is to encourage crews to be reflective and planful–to stop and think. This should overcome what Diehl (1991) calls the hazardous attitude of impulsiveness. Obviously, the crew must still first evaluate the situation and ask, Is a quick response necessary? If yes, do it! If not, buy time and develop a plan. For example, a crew might need to request a holding pattern or longer vectors to give them time to gather needed information or to fix a problem. Candidate decisions need to be evaluated by "what if" reasoning—If we do (or don't do) X, what will happen? A critical issue is how to teach good judgment. The crew must figure out how much information is needed, how many options should be considered, and when to say, "This decision is good enough," and stop deliberating. An equally important goal is cognitive economy, that is, training crews to make the best decision with the least cost in terms of effort and time.

A related issue pertains to encouraging crews to use communication to build *shared problem models.* The intent is not simply to get crews to talk more; more is not necessarily better. High levels of talk contribute to workload. What is desired is explicit discussion of the problem: its definition, plans, strategies, and relevant information. Current training programs that are integrating CRM with technical training encourage crews to use pre-briefings to assure that all members know what to do in case of time-critical emergencies, such as how to handle aborted take-offs. All crewmembers need encouragement to contribute to these shared models because most cockpit situations are dynamic and conditions may change rapidly. The entire crew needs to be kept up to date, and plans may need to be revised. The consequences of failed communications are evident in accident reports; specific findings have been summarized by Goguen, Linde, & Murphy (1986).

The possibility of training crews to communicate more effectively was demonstrated by Lassiter, Vaughn, Smaltz, Morgan, & Salas (1990). Instructors demonstrated various aspects of communication, including those we have defined as relevant to building shared problem models—closed-loop communication, mission-relevant talk, timeliness, volunteering of necessary information, requesting clarification, providing reinforcement, feedback, and confirming vital information. Demonstration of these skills was found to be more effective than didactic classroom instruction (simply telling the students what they should do). Line-oriented flight training or line-oriented simulation training provides crews opportunities to practice these communication skills.

A final set of skills that support the decision-making process is task and *resource management* skills. Overall crew performance depends on the captain's ability to prioritize tasks and allocate duties. But decision-making per se appears to depend more on the captain's ability to free him or herself from demanding tasks, like flying the plane. If they cannot do so, as in a two-member crew, they need to devise other strategies to keep themselves free and delegate tasks to the first officer. Demands can be managed by contingency planning, but this depends on the captain having a long enough time horizon and anticipating possible problems. This in turn depends on good situation awareness and metacognitive skill.

Two other general points about training skills that support decision-making:

1. Most critical is crew performance under time pressure, high workload, and other stressful conditions. If we expect crews to function well under those conditions, they must be trained under those conditions, as Butler points out in his chapter. Various levels of simulated environments could be used to create appropriate conditions without incurring risks.
2. If airlines are concerned about crew decision-making, then they must train crews, not individuals, to make decisions together (Hackman, 1987). Crew training is critical because of the communication, coordination, and task allocation aspects of performance. However, certain component skills that should be practiced until they are automated, such as pattern recognition, could probably be trained individually.

CONCLUSIONS: WHAT DO WE STILL NEED TO KNOW?

While research has yielded knowledge about how people make decisions in dynamic natural contexts and about how to train certain categories of complex skills, efforts to improve crew decision-making are hampered by a lack of specific research knowledge.

- We still need a better understanding of the structure of decision tasks in the cockpit, the kinds of knowledge, skills, and strategies needed to meet those demands, and the potential weak links in responding to each of the decision types.
- We need better definitions of performance standards and criteria for

judging the quality of each type of decision. Normative models are convenient but inappropriate to the dynamic time-pressured, knowledge-based reasoning in the cockpit. Reliable and valid measures of the skills that support decision-making are also needed.

- A better definition of which decision-relevant skills can be automated is needed.
- More knowledge is needed about the effects of various stressors, such as workload, fatigue, boredom, noise, or temperature extremes on crew (as opposed to individual) decision performance.

One final cautionary note: Formal decision models are seductive as the basis for training crew decision-making. These models offer optimal decisions and can be used as a benchmark against which to evaluate crew performance. The problem is that the assumptions of the formal models do *not* fit the conditions of the cockpit (especially the dynamically changing information, multiple goals, and lack of complete information). Furthermore, there is no evidence that using formal models will result in better crew performance. Encouraging crews to approximate normative reasoning in training programs (or stamping out useful heuristics) could undermine crews' positive use of their experience, knowledge, and skill. More fruitful approaches will build on the strengths the crews bring to the tasks and emphasize decision-making that supports effective flight performance.

Acknowledgments

The author's research was supported by the National Aeronautical and Space Administration (NASA), Office of Space Science and Applications, and by the Federal Aviation Administration (FAA).

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