Flight Crew Decision-Making

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Introduction

Flight 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 decisions 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 after the de-ice time had expired 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, the Canary Islands (Dutch Aircraft Accident Inquiry Board, 1979). However, commercial aviation remains an incredibly safe mode of transportation, in good part due to the skills and judgment of its pilots.

While an industry-wide analysis showed that over 70% of aviation accidents resulted from crew coordination or communication problems (as opposed to lack of individual technical skills, Lautman & Gallimore, 1987), the analysis of 37 aircraft accidents between 1978 and 1990 in which flight crew behavior contributed to the accident, the National Transportation Safety Board (NTSB, 1994) found that 25 involved what the Board considered “tactical decision errors.” Line Operations Safety Audits (LOSA) involving observations of crew behavior during “normal” flights found that decision errors were among the least likely type of error to occur (~6%), but were more likely (along with proficiency errors) to become consequential (e.g. result in a hazardous aircraft state) than other types of errors (Klinect et al., 1999). Hence, maintaining safe flight operations depends on assuring effective crew decision-making, especially under threatening conditions (Helmreich et al., 2001).

Because decision-making takes mental energy and because a large body of research suggests that people do not always make optimal decisions, aircraft designers, carriers and the FAA try to simplify crew decision-making by establishing standard procedures and checklists to cover anticipated failures or emergencies (Billings, 1991; Wiener, 1988), and through crew training and automated systems. However, poor decisions may occur even when problem situations are fairly straightforward because of conditions that increase risk, such as high workload, weather or heavy 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). Given the impossibility of designing error-proof or fully automated systems that can cope with any and all emergencies, the last line of defense is the flight crew. Thus, the bottom line is: How can flight crews be trained and supported to make the best decisions possible, especially under challenging high-risk conditions? To address this question, we first must ask: How do crews typically
make decisions? What constitutes effective decision-making? What factors make decisions difficult and contribute to poor decisions?

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 and choice of a course of action that satisfies goals while managing risks. However, decisions differ in the degree to which they call upon different types of cognitive processes. A decision to abort a takeoff 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 developed? How much time is available? Given the variety of decisions that are made routinely in the flight deck no single approach can be prescribed. No silver bullet exists to make crews better decision-makers. The long answer to the above questions is the subject of this chapter.

Since the original version of this chapter appeared in 1993, the concept of decision-making in the cockpit has evolved, deepening its roots in the naturalistic decision-making (NDM) framework and growing toward the goal of threat and error management (TEM). Perhaps the biggest change in aviation decision-making (ADM) over the past 16 years is the concept of ADM as risk management. This shift emphasizes the importance of risk perception and risk assessment as essential components of effective decision-making. It also aligns error detection and correction with ADM, in keeping with the TEM framework (Helmreich, 2002).

In this chapter the term ADM refers to decision-making by a flight crew, usually consisting of two members, but also includes solo pilots of varying skill levels and aircraft capabilities.

This chapter is organized as follows: first, the processes by which flight crews make decisions are described; then we address factors that contribute to decision difficulty and poor decisions, followed by factors that provide crew resilience in the face of high-risk challenges. The final section explores strategies for improving crew decision-making.

### 5.1. Aviation Decision-Making

Aviation decision-making is viewed in this chapter as a form of “naturalistic decision-making” (NDM) (Klein et al., 1993). Naturalistic decision-making focuses on understanding how people with domain expertise use their knowledge to make decisions, typically in safety-critical environments (Cannon-Bowers et al., 1996;
Zsambok & Klein, 1997). Certain features characterize naturalistic decision-making and distinguish it from classical analytical decision-making (Lipshitz et al., 2001). According to Lipshitz et al., its essential characteristics are: (1) *choice* (conceptualizing decision-making as choosing among concurrently available alternatives), (2) *input–output orientation* (focusing on predicting which alternative will, or should be, chosen given a decision-maker’s preferences), (3) *comprehensiveness* (conceptualizing decision-making as a deliberate and analytic process that requires a relatively thorough information search, particularly for optimal performance), and (4) *formalism* (the development of abstract, context-free models amenable to quantitative testing).

In contrast, in the NDM approach emphasis is placed on situation assessment prior to choosing a course of action; a process orientation replaces the input–output orientation; satisficing (i.e. achieving a “good enough” rather than optimal solution) replaces comprehensiveness and optimality; and context-sensitive informal models replace formalism (Lipshitz et al., 2001). These shifts stem from the fact that human information processing limitations\(^1\) preclude exhaustive information search and simultaneous comparison of multiple options. Moreover, in many high-risk consequential environments, time for making a decision is limited, information is incomplete, conditions change dynamically, and goals shift, rendering analytic decision-making impractical, if not impossible.

In NDM, decisions are integral to a task and are made in order to achieve operational goals, such as transporting passengers to their destinations while managing any threats to safety. The decision-maker’s knowledge, often acquired through many years of training and experience, plays a key role in the decision process. Knowledge is the basis for recognizing situations that require decisions to be made, assessing the type and degree of threat present, determining what information is relevant to the decision, and deciding on an appropriate course of action. Also, team members, when present, expand the cognitive resources and help to overcome potential limitations of a single decision-maker.

### 5.1.1. Theoretical Foundations

Several naturalistic decision models contributed to the ADM model described in this chapter. Four were especially influential: Klein’s (1993a) Recognition–Primed Decision (RPD) model, Hammond’s Cognitive Continuum theory (Hammond et al., 1987),

\(^1\) Simon (1991) has termed this “bounded rationality.”
Rasmussen’s (1993) Levels of Cognitive Control model, and Cohen’s (Cohen et al., 1996) Recognition/Metacognition model. Each model contributed in the following ways to the aviation decision model.

**Klein—Recognition Primed Decision-Making**

Klein’s notion of how domain-specific knowledge guides recognition of situations and retrieval of appropriate responses is the foundation for many aviation decisions, especially those made under time pressure. Schema-based knowledge provides the link between recognizable situation patterns and actions that have worked in the past under similar conditions; this knowledge also is the basis for mentally simulating outcomes of the actions.

**Hammond—Cognitive Continuum Theory**

This theory asserts that decisions vary from intuitive to analytic depending on the nature of the situations in which they are made. In intuitive decisions, people rely on pattern matching; in analytical decisions, they use more thorough evaluation processes. Accompanying this continuum is a *task* continuum that reflects the nature of the cues available to the decision-maker. The amount and type of data determine where a problem sits on the continuum. According to Hammond, good decisions depend on correspondence between the decision strategy and the task: an analytical strategy applied to non-engineered cue patterns is inefficient, whereas an intuitive strategy applied to numeric data may be suboptimal.

**Rasmussen—Levels of Cognitive Control**

Rasmussen’s (1985, 1993) Cognitive Control model distinguishes between skill-based, rule-based and knowledge-based behaviors. Skill-based behaviors are highly practiced and exercised automatically in response to changes in cue input. Rule-based behaviors involve conscious action, but typically are codified in standard procedures. Knowledge-based behaviors involve deliberate thinking that is needed when skill- and rule-based guidance is lacking. Analytic or choice decisions and creative problem-solving fall into this category.

**Cohen—Recognition/Metacognition Model**

Some form of control process is needed to manage the shifts along a cognitive continuum, levels of cognitive control and types of recognitional processes. Cohen et al. (1996) formalized a critical thinking model that combined recognitional and
Figure 5.1 Schematic of aviation decision process model in response to an environmental threat. Decision processes are shown as a function of environmental conditions pertaining to cue diagnosticity and familiarity, time pressure, and risk, as well as response affordances: availability and familiarity of response options.

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metacognitive processes. The recognition component involves a quick test to assess situation familiarity and problems with the retrieved solution, time available to make a decision and the stakes if an error is made. If no problems are found, then the RPD-elicited response is adopted. But if stakes are high, time is available and the problem is atypical, then the metacognitive component is invoked. It provides a basis for critiquing and correcting the problem definition and solution until the decision-maker is confident of the best interpretation and solution. Cohen’s quick test for problem familiarity, time and stakes maps closely to the situation assessment processes in the ADM model depicted in Figure 5.1.
5.1.2. The Role of Expertise

Expertise contributes to cockpit decision-making in three ways. First, expert knowledge facilitates rapid and accurate perception of cues and interpretation of problems (Cannon-Bowers et al., 1990). Second, this knowledge includes stored condition–action patterns, the basis for recognition-primed decisions (Klein, 1989, 1993). Third, expert knowledge provides a basis for risk assessment and for estimating the likelihood of occurrence of various kinds of problems.

Knowledge is not a shield against errors. Expertise is the foundation for heuristics, which sometimes result in poor judgments. Deep knowledge is responsible for efficient functioning most of the time, but occasionally leads one astray.

Expert knowledge confers an advantage primarily for problems that are meaningful within the expert’s domain (Klein, 1998). Chess masters show remarkable memory for the location of chess pieces that represent positions during play, a basis for strategic moves (Chase & Simon, 1973). But if those same pieces are placed randomly on the chessboard, the masters’ recall is no better than the novice’s.

5.1.3. Aviation Decision Process Model

The aviation decision-making model described in Orasanu (1993) still holds, with some minor adjustments as shown in Figure 5.1. Using NDM research methods, Orasanu and Fischer (1997) analyzed aviation incident reports (from the NASA Aviation Safety Reporting System, ASRS), National Transportation Safety Board (NTSB) accident reports and observations of flight crews in complex flight simulations to develop an aviation decision process model. The model involves two major components: situation assessment (SA) and choosing a course of action (CoA).

Situation Assessment

Aviation decisions typically are prompted by off-nominal or changed conditions that require adjustment of the planned course of action. Situation assessment involves defining the problem, assessing the level of risk associated with it and determining the amount of time available for solving it. Available time appears to be a major determinant of subsequent strategies. If the situation is not understood, diagnostic actions may be taken, but only if sufficient time is available. External time pressures may be mitigated by crews to support information search and problem solution (Orasanu & Strauch, 1994), e.g. crews may buy time through holding, or reprioritize tasks to reduce workload.
(cf. Wickens & Raby, 1991). If risk is high and time is limited, action may be taken without thorough understanding of the problem.

**Risk Assessment**

Perhaps the most significant elaboration of the ADM model since 1993 is increased attention to the risk assessment component of situation assessment. In order to manage risk, threats must be perceived and accurately assessed. Risk includes two components: the likelihood of a threat and the severity of its potential consequences. The two vary independently, although in aviation, events with the most severe consequences typically occur quite infrequently. These include engine failures, fires and other emergencies. Other threats are more common, such as traffic, weather and schedule delays, but strategies for their management are more accessible.

While relatively little research has been conducted on risk perception in aviation (but see O’Hare and Smitheram, 1995), Fischer et al. (2003) conducted a study that clearly demonstrated the role of risk perception in decision-making. Using a think-aloud protocol with dynamically evolving ambiguous flight situations, the investigators analyzed the information pilots requested, their evaluation of conditions in terms of risk, sensitivity to ambiguity, time available and goal conflicts, and ultimate decisions and risk management strategies. Findings showed that decisions—either accepting or avoiding risks—depended on how the pilots perceived the ambiguous conditions. If they felt conditions were not too severe, they were willing to take a risk, but if the risk level passed a threshold, they avoided the risk.

**Choosing a Course of Action**

After the problem is defined and the conditions are assessed, a course of action is chosen based on the structure of the options present in the situation. Building on Rasmussen (1985), Orasanu and Fischer (1997) specified three types of response structures: rule-based, choice and creative. All involve application of knowledge but vary in the degree to which the response is determined by the situation. What constitutes an appropriate course of action depends on the affordances of the situation. Sometimes a single response is prescribed in company manuals or procedures. At other times, multiple options exist from which one must be selected. On some rare occasions, no option is readily available and the crew must invent a course of action. In order to deal appropriately with the situation, the decision-maker must be aware of what constitutes a situationally appropriate process.

While various types of decisions can be distinguished for analytical purposes, in practice any given flight situation may require the 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.

5.1.4. Situational Constraints and Affordances in Choosing a Course of Action

Rule-based or RPD decisions

Single-response situations correspond to Klein's (1989, 1993a) recognition-primed decisions and Rasmussen’s (1985, 1993) rule-based actions. Single option cases are the simplest decisions because they require the least cognitive work.

In many high-risk and time pressured situations, such as smoke in the cockpit, an engine stall, or rapid decompression, an action is prescribed in response to specific situation cues. These and other abnormal situations are deemed to be sufficiently consequential that procedures are specified to reduce the crew’s need to invent solutions for the problem. The primary decision is whether any circumstances suggest that the pre-defined response should not be implemented.

Sometimes an action may be planned or in process and a stimulus triggers a decision to terminate the action, a go/no go decision. Stimulus conditions that elicit this response may be quite diverse. For example, a rejected takeoff may be triggered by an explosive engine failure, cargo door light, runway traffic, compressor stall, or engine overheat lights (also see Chamberlin, 1991). Likewise, a missed approach—a decision to terminate a landing—may be triggered by inability to see the runway at decision height, by air or ground traffic, autopilot disengagement, or an unstable approach.

All rule-based decisions involve risk assessment, particularly when ground speed or altitude is near a decision threshold. Certain conditions, like a wet runway or system malfunction that result in poor braking, will complicate the decision.

Decision-making in aviation differs from many other high-consequence domains such as medicine or fire-fighting in that many rule-based aviation decisions are codified in FAA regulations or company operations manuals. In other domains the basis for condition–action pairings is the decision-maker’s experience, which builds deep domain knowledge. Klein (1989, 1998) found that experienced decision-makers recognize a cue configuration as signaling a particular type of problem and then generate an appropriate response based on previous experience with similar problems. Once a response option has been retrieved, it is evaluated by mentally simulating its consequences to determine whether the response will satisfy the decision-maker’s goals. If so, the action is accepted. If not, another option is generated and evaluated, or the situation is reassessed.
Multiple-option decisions

Some flight decisions involve choice from among alternatives present in the situation. These choices map most closely onto our everyday notion of decision-making. For example, a crew may need to select an alternate landing site in response to an on-board medical emergency in bad weather. Landing alternates are prescribed in the flight plan if weather conditions at the destination deteriorate, and procedure manuals provide guidance on how to deal with medical emergencies. However, weather conditions may be deteriorating at the nearest airport that offers appropriate medical facilities, and precious time may be required to reach a different airport. In this case, the crew needs to weigh the risks of trying to land in borderline weather conditions versus the possible danger to the passenger of flying to a more distant airport.

Strategies used by crews to select from among alternatives vary, but observations to date (Klein, 1993a; Orasanu, 1993) suggest that they do not correspond to a full analytical procedure. A full analysis would involve evaluation of each possible option in terms of every variable relevant to the decision (e.g. weather, fuel consumption, runway length), 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 short-cuts in this process. They work toward a suitable—but not necessarily the best—decision in the shortest time, investing the least possible cognitive work.

Options often are 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 is essentially an elimination by aspects strategy (Tversky, 1972). However, if a few candidates are available, one is chosen to match the constraints of the circumstances and the crew’s goals and perceived risks. Usually, the most safety-critical constraint prevails. However, organizational policy also plays an important role. The crew may choose an alternate that has a company maintenance facility or where replacement planes will be available for passengers to continue their flight.

Ill-Defined problems

Two other 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 situation assessment. Ambiguous cues may make it impossible to define the problem that needs fixing. 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 (procedural management), or diagnose and define the problem, and then generate a novel solution (creative problem-solving) because no prescribed procedures exist for dealing with it.
Procedural management. Certain cues are ominous but leave the crew without a clear idea of the underlying problem. Various noises, thumps, vibrations, rumblings, pressure changes, or control problems indicate that something has happened, but not necessarily what. The 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. These problems are essentially treated as RPD situations, with the condition broadly labeled as “emergency landing.” A recent example of a procedural management decision was the landing on the Hudson River by a USAir A-320 aircraft after both engines were lost due to bird strikes on takeoff from LaGuardia Airport in New York (NTSB, 2009). Captain Sullenberger initially planned to land at Teterboro Airport in New Jersey after the dual engine loss, but realized they had insufficient altitude to travel the 6 miles; instead he opted to make a river landing.

The cognitive work done for this class of decision is primarily 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 diagnosis.

Diagnosis of the problem underlying ambiguous cues can serve two purposes. It can clarify what the problem is so that an appropriate action can be taken, or it can provide information that may be useful for fixing the problem. When workload is relatively low and time is available, the crew may try to diagnose and fix the problem. But even if diagnosis does not lead to fixing the malfunction, it can turn the problem into one with a better-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.

Creative problem-solving. Perhaps the most difficult types of decisions are those requiring creative problem-solving. In addition to diagnosing the situation, a solution must be invented that will satisfy the goal. These cases tend to be low-frequency events; neither aircraft designers nor operations personnel imagined such a situation would arise, so no procedures were designed to cope with them.

Diagnosis is critical and typically involves causal reasoning, which is reasoning backward from effects to cause, as well as hypothesis generation and testing. 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 often are embedded in checklists.

Even if the nature of the problem has been determined, no ready solutions are prescribed for these problems. Perhaps the most celebrated case of creative problem solving was United Airlines flight 232 (NTSB, 1990) in which the DC10 lost all hydraulic systems due to an explosion in the number two engine. The captain invested 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. 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 and power level to control the altitude.

While the case of UAL 232 is extreme, ASRS reports indicate that crews do, in fact, encounter novel situations that are not covered by the Federal Aviation Regulations (FARs), Minimum Equipment Lists (MEL), or checklists. For example, the 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 rather than land immediately, the crew came up with a creative solution. They descended to FL250 and borrowed the flight attendants’ walk-around oxygen bottles. (Different O₂ requirements are specified for flight attendants above and below FL250.) This solution allowed them to continue to their destination rather than to divert or to descend to 10,000 feet, which would have eliminated the need for the O₂. However, the latter option would have meant the flight would not have had sufficient fuel to reach its 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 were using the walk-around O₂ bottle, as it had 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 the possibility of a missed approach or diversion due to poor destination weather. 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 above effort to classify decisions in terms of situational demands and affordances is a first step toward understanding what makes certain kinds of decisions difficult, the cognitive effort they require and possible weak links. The various types of decisions fall on a continuum ranging from simple to complex, which require little cognitive work to
considerable effort. One reason for laying out these differences is to create an appreciation for the fact that no single decision method will work for all types of situations.

5.2. What Factors Make Decisions Difficult?

Before examining factors that make decisions difficult and contribute to errors, the concept of “decision error” within an NDM framework must be considered.

5.2.1. Decision Errors: Outcome vs. Process

Defining decision errors in naturalistic contexts is fraught with difficulties. First, errors typically are defined as deviations from a criterion of accuracy. However, defining the “best” decision in a natural work environment may be impossible. Second, a loose coupling of decision processes and event outcomes works against using outcomes as reliable indicators of decision quality. Redundancies in the system can “save” a poor decision from serious consequences. Conversely, even the best decision may be overwhelmed by events over which the decision-maker has no control, resulting in an undesirable outcome. A third problem is hindsight bias. Fischhoff (1975), Hawkins and Hastie (1990) and others point out a tendency to define errors by their consequences. But in natural contexts the analyst does not know how often exactly the same decision process was used or the same decision was made in the face of similar situations with no negative consequences. Were those prior decisions also “errors”?

Unsatisfying though it may be, the following definition is adopted here: decision errors are “deviations from some standard decision process that increase the likelihood of bad outcomes” (Lipshitz, 1997, p. 152). Although outcome alone may not be a good indicator of decision quality, the decision-maker’s goal or intended outcome remains important. In naturalistic work contexts, decisions contribute to performance goals. Decisions do not stand alone as events to be judged independent of the broader task.

5.2.2. How Can Decision Processes Go Wrong?

Decision errors may arise within the two major components of the aviation decision model: (a) pilots may develop an incorrect interpretation of the situation, which leads to an inappropriate decision, or (b) they may establish an accurate picture of the situation, but choose an inappropriate course of action. In addition, they may not appropriately assess the risks inherent in the situation.
Faulty situation assessment

Situation assessment errors can be of several types: cues may be misinterpreted, misdiagnosed, or ignored, resulting in an incorrect picture of the problem (Endsley, 1995); risk levels may be misassessed (Johnston, 1996; Orasanu et al., 2004); or the amount of available time may be misjudged (Keinan, 1988; Maule, 1997; Orasanu & Strauch, 1994). Problems may arise when conditions change and pilots do not update their situation models (Woods & Sarter, 1998).

For example, one accident that can be traced to an incorrect assessment of the situation was the decision by the crew of a B-737 to shut down an engine; unfortunately, the wrong one:

_The crew sensed a strong vibration while in cruise flight at 28,000 ft. A burning smell and fumes were present in the passenger cabin, which led the crew to think there was a problem in the right engine (because of the connection between the cabin air conditioning and the right engine). The captain throttled back the right engine and the vibration stopped. However, this was coincidental. In fact, the left engine had thrown a turbine blade and gone into a compressor stall. The captain ordered the right engine shut down and began to return to the airport. He again questioned which engine had the problem, but communication with air traffic control and the need to reprogram the flight management computer took precedence, and they never did verify the location of the problem. The faulty engine failed completely as they neared the airport, and they crashed with neither engine running._ (AAIB, 1990)

The problem was incorrectly defined because the cues (vibration and burning smell) supported the interpretation of a right engine problem. The crew did not verify this interpretation before taking an action that was irrevocable at that point in the flight.

Faulty selection of action

Errors in choosing a course of action may also be of several types. In rule-based decisions, the appropriate response may not be retrieved from memory, either because it was not known or because some contextual factor mitigated against it. Conversely, an inappropriate rule may be applied, especially a frequently used one. In choice decisions, options may not be considered. Constraints that determine the adequacy of various options may not be used in evaluating them.

Creative decisions may be the most difficult because they involve the least support from the environment; candidate solutions must be invented to fit the goals and existing conditions. Any solution that meets one’s goal may be considered a success. As Klein
(1993b) noted, decision-makers may not project the consequences and uncertainties associated with candidate actions, resulting in a poor choice of action.

An accident in which an inappropriate course of action was chosen in the face of fairly complete information about the nature of a problem occurred near Pinckneyville, IL.

About two minutes into a night flight in instrument conditions, a Hawker-Siddley commuter aircraft lost its left generator. In error, the first officer isolated the right generator and then was unable to restart it. This meant total loss of ability to generate electrical power, which was needed to run all cockpit instruments. Under the best of circumstances batteries might be expected to last for 30 minutes. The captain decided to continue to the destination airport 45 minutes away, rather than diverting. Continued use of non-essential electrical equipment shortened the battery life. A complete electrical failure and subsequent loss of flight instruments critical for IFR flight led the plane to crash. (NTSB, 1985)

The crew’s decision to continue as planned despite the mechanical failure, rather than to land as soon as possible, was fatal.

Decision difficulties arise when goals conflict or when no good choice is available. For example, weather at the destination airport might be satisfactory when the plane takes off, but may deteriorate rapidly and be below minimums by the time the flight arrives. The alternative airport 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. 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, the weather is changing over time and their location is changing over time.

Faulty Risk Assessment

Poor decisions may also arise when a flight crew is aware of conditions that require a decision, but underestimates the level of risk associated with the conditions, especially when they are changing dynamically. For example, when approaching Dallas for landing, the first officer of an L-1011 commented on lightning in the storm lying on their flight path (NTSB, 1986a). Yet, the crew flew into it and encountered wind shear. We know that risk is important to pilots, because potential risk was the dominant dimension considered by captains from several airlines when making judgments about flight-related decision situations (Fischer et al., 1995). Why then do crews appear to underestimate risk in potentially critical situations?
One possible explanation is that crews lack the relevant experience or are unable to retrieve the knowledge needed to assess risk appropriately in those specific circumstances (cf. Klein, 1993b). Another arises from pilots’ routine experience. If similar risky situations have been encountered in the past and a particular course of action has succeeded, the crew will expect to succeed the next time with the same response, a phenomenon Reason (1990) called “frequency gambling.” Given the uncertainty of outcomes, in many cases they will be correct, but not always. Hollenbeck et al. (1994) found that past success influences risk-taking behavior. Baselines become misrepresented over time as a situation becomes familiar and the individual becomes more comfortable with it. Likewise, Sitkin (1992) argued that uniformly positive experiences provide no baseline by which to determine when the situation is becoming more dangerous.

5.2.3. Plan Continuation Errors (PCE)

Examination of decision errors in the NTSB’s (1994) analysis of 37 crew-involved accidents revealed an emergent theme: about 75% of the decision errors involved continuation of the original flight plan in the face of cues that suggested changing the course of action (Berman, 1995). These included taking off in snowy conditions, landing during an unstable approach, or continuing a VFR flight in instrument conditions (cf. O’Hare and Smitheram, 1995). More recent analyses confirm this pattern, called ‘plan continuation errors’ (Orasanu et al., 2002) or plan continuation biases (Dismukes et al., 2007).

Although it is not possible to determine the cause of these patterns from post hoc analyses, our efforts were drawn to examining factors that might lead crews to demonstrate plan continuation types of decisions. In many cases it appeared that the crew failed to appreciate the risks inherent in the evolving conditions or those associated with pressing on with their original course of action. Both contextual and cognitive factors were hypothesized as potential contributors to these types of decision errors.

5.2.4. Error Inducing Contexts

Three types of contextual factors extracted from accident analyses may contribute to poor aviation decision, including PCEs: (1) poor quality information, including ambiguous dynamic conditions or poorly displayed information, (2) organizational pressures, and (3) environmental threats and stressors.
Information quality

Cues that signal a problem are not always clear-cut. Poor interface design that does not provide adequate diagnostic information or action feedback can lead a crew astray (Woods & Sarter, 1998). For example, in the Kegworth crash, information about which engine had the problem was poorly displayed, contributing to the flight crew shutting down the wrong engine (AAIB, 1990). Conditions can deteriorate gradually, and the decision-maker’s situation awareness may not keep pace. Ambiguous cues permit multiple interpretations. If ambiguity is not recognized, a crew may be confident in their understanding of a situation, when in fact they are wrong.

In addition to making it difficult to assess the situation, ambiguity can influence the decision indirectly. A crewmember may recognize that something “doesn’t seem right” (as stated by the first officer in the Air Florida takeoff crash in Washington, DC, during heavy snow with a frozen pitot tube, NTSB, 1982), but may find it difficult to justify a change in plan when cues are ambiguous. For decisions that have expensive consequences, such as rejecting a takeoff or diverting, the decision-maker may need to feel very confident that the change is warranted. Ambiguity thus may contribute to plan continuation errors.

Organizational pressures

An organization’s emphasis on productivity may inadvertently set up goal conflicts with safety. As Reason (1997) has documented, organizational decisions about levels of training, maintenance, fuel usage, keeping schedules, etc. may set up latent pathogens that undermine safety. For example, on-time arrival rates are reported to the public. Companies also emphasize fuel economy and getting passengers to their destinations rather than diverting, perhaps inadvertently sending mixed messages to their pilots concerning safety versus productivity. Mixed messages, whether explicit or implicit in the norms and organizational culture, create conflicting motives, which can affect pilots’ risk assessment and the course of action they choose.

Environmental Threats and Stressors

Operational factors that may affect pilots’ ability to make reasoned decisions include high workload, limited time, heavy traffic, poor weather, last minute runway changes, and schedule delays. An extensive literature documents the deleterious effects of stress on cognitive functioning (Hancock & Desmond, 2001; Hockey, 1979), including attentional focus, working memory capacity, and risk taking. These influence decision
process through their effects on information scanning, cue detection, hypothesis
generation, and option evaluation. Stress also may affect crew communication, which
can interfere with building situation models, sharing information, contingency
planning, and error trapping.

One of the few studies to examine stress and pilot decision making found that
stress had little effect on decisions that drew on domain expertise and relied on
perceptual knowledge, i.e., recognition-primed decisions (Stokes et al., 1997). This is
consistent with the notion that decisions are more difficult when the problem is not
well understood and no clear response is available, i.e., in ill-defined problem
situations.

Certain phases of flight typically induce higher levels of stress due to heavy workload,
traffic and little room for error recovery (Strauch, 1997), such as during takeoff and from
top of descent to landing. Under stress, decision-makers often fall back on familiar
responses (Hockey, 1979), but these responses may not be appropriate to the situation.
For example, about one minute after takeoff the captain of a four-engine aircraft
retarded power on all four engines in response to a vibration throughout the aircraft, an
action that resulted in a crash (NTSB, 1986b). Reducing power so close to the ground
was not appropriate because insufficient time was available for recovery. The same action
might have been fully appropriate at a higher altitude.

Other potentially dangerous conditions may permit more time to diagnose the
problem and consider what to do (e.g. fuel leaks, or hydraulic, electrical or
communication failures). However, under stress, people often behave as though they
are under time pressure, when in fact they are not (Keinan, 1988).

5.2.5. Cognitive Factors

Ambiguous cues, dynamically changing risks, organizational pressures and
environmental stressors may not in themselves be sufficient to cause poor decisions.
However, when the decision maker’s cognitive limits are stressed, these factors may
combine to induce errors.

Schema-based decisions

Consider that more than one half of the decision errors in the NTSB (1994) database
(29 out of 51) involved omissions, or failures to do something that should have been done.
Crews may have been captured by a familiar schema in these cases, leading them to
do what they normally do, that is, to carry on with the usual plan, even though another
action was called for. Guidance by routine knowledge also supports the “cognitive miser” perspective: people will do as little as possible to get the job done at a satisfactory (though not necessarily optimal) level, Simon’s (1957) concept of “satisficing.”

Lack of knowledge

A cognitive economy or a schema dominance explanation, however, fails to account for errors of commission (NTSB, 1994). These are cases in which crews took actions that were out of the ordinary, such as attempting to blow snow off their aircraft using the engine exhaust from the aircraft ahead of them (NTSB, 1982). These cases may reflect “buggy” mental models or gaps in knowledge (VanLehn, 1990). Buggy models may lead to success in some cases, so decision-makers may have great confidence in these inadequate models.

Novices are at a disadvantage in making decisions because they lack the deep and well-integrated knowledge of experts (Chi et al., 1988; Klein, 1998). This may be manifest in what appears to be inadequate situation assessment or choice of risky options. For example, Driskell and colleagues (1998) found that general aviation (GA) pilots only matched experts’ choices of options under a variety of flight conditions in terms of their “riskiness” 50% of the time. One reason may be their less-informed risk models. When Fischer et al. (2003) asked GA and commercial pilots to categorize flight scenarios on the basis of risk, novices focused only on the severity of the consequences, whereas experts included both the timeline (How long do I have to make a decision?) and controllability (What can I do about the situation?).

Expert–novice differences were manifest in behaviors of more and less experienced pilots in several low-fidelity simulations involving deteriorating weather conditions. More experienced pilots made decisions earlier and traveled less into bad weather prior to diverting than did less experienced pilots (Wiegmann et al., 2002), suggesting inadequate situation awareness stemming either from lack of knowledge or different risk standards in the more junior pilots.

Social factors

Social factors may create goal conflicts that increase decision difficulty. Perceived expectations among pilots may encourage risky behavior or may induce one to behave as if one were knowledgeable, even when ignorant. For example, a runway collision in near zero visibility (due to fog) resulted when one aircraft stopped on an active runway because the crew did not realize where they were (NTSB, 1991). The captain was unfamiliar with the airport and was making his first unsupervised flight after a long
period of inactivity. The first officer boasted of his knowledge of the airport but, in fact, gave the captain incorrect information about taxiways. Rather than questioning where they were, the captain went along.

Based on critical incident interviews with pilots flying in the extreme conditions of Alaska, Paletz and colleagues characterized several social phenomena that may lead crews into taking risks and perhaps plan continuation errors (Paletz et al., 2009). These include:

- **Informational social influence**: accepting information obtained from another as *evidence* about reality, as in follow-the-leader behavior
- **Foot-in-the-door persuasion technique**: agreement to a small request increasing likelihood of agreement to a large one later
- **Normalization of deviance**: an incremental acceptance of a progressively lower level of safety by a group of people
- **Impression management**: not looking bad to themselves or to others
- **Self-consistency motives**: acting in ways consistent with one’s beliefs.

## Personal Stress

Personal stressors include concern with family matters, job security, or health issues. While some pilots may be able to put these matters out of mind on the flight deck, others may be distracted by them. These personal factors may also affect decision making by interfering with sleep, which can have negative effects on alertness, attentional focus, mood, and crew communication. Ill-structured problems and organization-related goal conflicts require high levels of cognitive effort, which may be compromised in conjunction with other stress factors (Cannon-Bowers & Salas, 1998). Stress typically constrains working memory capacity (Hockey, 1979), thus limiting the decision-maker’s ability to entertain multiple hypotheses or to mentally simulate the consequences of options (Wickens et al., 1993).

### 5.3. Behaviors that Characterize Effective Crew Decision-Making

Behaviors associated with effective crew decision making have been identified from research in both high- and low-fidelity flight simulations (Orasanu, 1994), and validated
in actual line operations, primarily through line operational safety audits (LOSA) (Thomas, 2004). Both sources provide evidence of how crews manage threats, trap errors, and maintain positive crew climate essential to making good decisions. These behaviors can be broken down into taskwork skills and teamwork skills.

5.3.1. Taskwork Skills

*Situation Awareness.* Effective crews are vigilant. They monitor the environment for threats that may require a response, as well as monitoring progress of the flight according to the operative plan. They gather additional information to clarify threats.

*Build Shared Situation Models.* Effective crews build shared situation models when threats arise. They assess and communicate the nature of the threat, the degree of risk, and time available.

*Update Plans.* Effective crews are adaptive. They adjust to dynamically evolving conditions and update plans as needed (to avoid plan continuation errors). This includes building contingency plans to cope with uncertain situations. Threats may require that goals be updated to support threat management while maintaining the overall plan.

*Manage Tasks and Workload.* Effective crews revise task priorities and reassign tasks to manage workload.

*Evaluate Options.* Effective crews project the consequences of potential decisions to decide what to do. They are sensitive to competing goals and risks, such as safety, productivity, economic and professional consequences.

*Metacognitive Strategies.* Effective crews are reflective. They check their assumptions, question missing information, consider what might go wrong, how likely it is and how serious it would be.

5.3.2. Teamwork Skills

Effective taskwork depends on effective teamwork. Maintaining a positive crew climate and trust in each other is essential for assuring that all crewmembers, especially junior ones, contribute to problem assessment and decision making (Salas et al., 2005). Trust and openness are the basis for error trapping. Accident investigations consistently point out the role of “monitoring-challenging” failures as links in the accident chain (NTSB, 1994). These failures are more frequent when the captain is the one making the error than when both crewmembers are responsible or when the error arises outside of the flight deck (Orasanu et al., 1998; Thomas, 2004).
Crew Climate. Positive crew climate begins with the captain’s pre-flight briefing (Ginnett, 1993), which establishes a climate of openness and participation. Studies show that effective crews are characterized by active participation of all crewmembers (Fischer et al., 2007; Parke et al., 2000).

Error Trapping. When errors occur, members of effective crews are able to disrupt the error chain by calling out the error and correcting it (or even preventing it from occurring by being pro-active). Junior crewmembers are more likely to be effective in trapping errors made by the captain by using certain communication strategies: clearly describing the nature of the problem, offering a suggestion for solving it while leaving the decision up to the captain, and providing justification for the suggestion (why it’s a good idea) (Fischer et al., 2000). Challenges that are too direct or too mitigated (weak) are not likely to be effective, the former because they may disrupt crew climate, the latter because they don’t convey the seriousness of the problem. Effective challenges invoke a crew orientation (“we’re in this together”), reflected by use of “we” rather than “you” or “I” in the suggestions, e.g., “We need to turn 15 degrees north about now.”

Back-up Strategies. Finally, members of effective crews monitor each other for stress, fatigue or workload and back up each other or reassign tasks as needed. Good crews use compensatory strategies to manage fatigue or stress, such as double-checking information, status or plans (Petrilli et al., 2006).

5.4. Can We Train Crews to Make Better Decisions?

Team training approaches that focus on team process skills appear to be most effective in developing resilient teamwork skills essential to effective crew decision making (Klein et al., 2008; Salas et al., 2007). At this point, no basis exists for believing that it is possible to develop training to improve all-purpose decision-making skills. Decision strategies are learned most effectively in conjunction with domain-specific content (Glaser & Bassok, 1989), a reality guiding the integration of CRM skills with technical training for pilots under the FAA’s Advanced Qualification Program (AQP) (FAA, Advisory Circular #120-54A, 6/23/06). Team training approaches that focus on team process skills appear to be most effective in developing resilient teamwork essential to effective crew decision making (Klein et al., 2008; Salas et al., 2007). Positive evidence is accruing on the success of training in the perceptual skills and strategies needed for effective situation assessment (Endsley & Robertson, 2000; Wiggins & O’Hare, 2003).
5.4.1. Aviation Decision Training Models

Several decision training models have been developed in the aviation industry, two of which are used by major international carriers. DODAR stands for Diagnosis, Options, Decide, Assign tasks, Review (Walters, 2002). FOR-DEC stands for Facts, Options, Risks and Benefits—Decide, Execute, Check (Hoermann, 1995). While both include steps of gathering information, deciding on the basis of anticipated consequences, and reviewing the decision, neither capitalizes on the crew’s expertise at recognizing and sizing up the situation, as in NDM. Both imply concurrent weighing of multiple options. Neither is tuned to differences in decision situations for which different decision strategies are appropriate (i.e. rule-based, choice and creative decisions). Essentially, these remain domain-independent general approaches that could be applied in any domain by any decision-maker.

5.4.2. NDM-based training

In contrast, training grounded in the NDM framework provides opportunities for developing rapid pattern recognition, serial consideration of options, use of mental simulation to evaluate options, and metacognitive skills (Cohen et al., 1996; Means et al., 1993; Klein, 1993a). Klein (1998) has pointed out that learning to think like an expert involves developing deep knowledge that serves as a basis for making decisions. He recommends the following activities to foster this learning:

- Engaging in deliberate practice that includes a goal and evaluation criteria
- Building an extensive experience bank from diverse scenarios
- Obtaining feedback that is accurate, diagnostic and timely
- Reviewing prior experiences to derive new insights and lessons from mistakes.

Situation assessment

Training within an NDM framework emphasizes development of situation assessment skills, an element that was totally absent from traditional decision models. For aviation decisions, both rapid pattern recognition and diagnostic skills are needed. Recognition of danger cues and generation of appropriate responses to them should become automatic, which can only happen through repeated practice with feedback. Deliberate rather than recognitional situation assessment skills are required when cues are ambiguous, contradictory or worrisome. Risk assessment is an essential component.
Course of action selection

The second major component of training within an NDM framework is evaluating a course of action. In most cases a workable rather than an optimal solution may be adequate. In the case of a rule-based or RPD decision, the option is generated upon recognition of the situation. Its adequacy in meeting the decision-maker’s goals is evaluated by using mental simulation of the likely outcome of taking the action in that specific context. Training needs to emphasize that evaluating one option at a time is appropriate under many circumstances rather than generating and assessing all possible options, especially under time-pressured situations.

Metacognitive training

Perhaps the most trainable decision-related skill complex is metacognition. Considerable research exists supporting the trainability of these skills across wide ranges of populations (Brown et al., 1986). Training strategies developed by Cohen, Freeman and Thompson (1998) emphasize goals, environmental conditions and actions under realistic practice conditions to promote accurate recognition, and repetition with feedback to facilitate automatic performance. It aims to sensitize trainees to domain-specific cues including time constraints, stakes and problem familiarity, as well as conflicts, completeness and reliability of information. Practice involves making metacognitive processes explicit (i.e. critiquing and correcting), which benefits from a team context. Devil’s advocate and crystal ball techniques are used to challenge assumptions and see weaknesses in situation assessments and plans.

Thus, crews are prepared to cope when complications arise from multiple or competing goals, e.g. maintaining flight safety, saving fuel and getting the passengers to their destinations on time, with different options satisfying these competing goals. Crews learn to recognize that some level of risk always exists and that tradeoffs must be managed. Metacognitive assessment includes oneself: Are you fatigued or stressed? What are your motives in pursuing a particular option? Senders and Moray (1990) noted that pilots need training in “how to change one’s mind” and avoiding cognitive “lockup,” which may play a role in plan continuation errors.

5.4.3. Communication training

Build Shared Situation Models

As unexpected dynamic conditions arise, it is essential that team members communicate to build a shared model of the emergent situation and how to cope with it: What is the
problem? What is our plan? Who does what and when? What contingencies must be planned for? What cues or conditions must we look out for and what will we do? Only if all participants have a shared model will they be able to contribute efficiently to the shared goal. 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 takeoffs.

**Establish a positive crew climate through briefings**

Briefings conducted by the captain go a long way to assure that team members understand their role in the effort and feel comfortable offering their contributions, which may be critical to managing threats in challenging situations (Ginnett, 1993). Briefings set the tone or team climate; in both aviation and in medicine team members “follow the leader,” adopting the interactional style of the leader (Lingard et al., 2002). Salas et al. (2005) point out the importance of mutual trust in supporting mutual performance monitoring essential to flight safety. By establishing positive relationships, the leader can let the team know that she or he is not invincible and create a crew climate that is open and productive.

**Monitor and challenge threats and errors**

Crewmembers also must learn appropriate ways to bring problems to the attention of the captain (called advocacy and assertion in early CRM parlance). These include being as specific as conditions allow, pointing out problems, suggesting solutions and providing reasons for one’s concerns. Strategies identified by Fischer and Orasanu (1999, 2000) to be most effective in correcting errors involved crew obligation statements (such as “We need to deviate right about now”), preference statements (e.g. “I think it would be wise to turn left”) and hints (e.g. “That return at 25 miles looks mean”). In addition, requests that were supported by problem or goal statements (e.g. “We need to bump the airspeed to Vref plus 15. There’s windshear ahead.”) were rated as more effective than communications without supporting statements.

**5.4.4. Monitoring skills**

The above communication skills focus on how to communicate. They are predicated on adequate skill in monitoring threats in the environment and crew errors. Sumwalt et al.
(2002) recommend training for monitoring that focuses on specific areas of vulnerability, such as top-of-descent or points at which clearances are expected. Non-critical tasks should be accomplished during less critical phases. Monitoring other crewmembers is essential to mutual back-up behaviors.

Effective monitoring thus depends on effective workload and task management strategies. Overall crew performance depends on the captain’s ability to prioritize tasks and allocate duties. Demands can be managed by contingency planning, but this depends on the captain anticipating possible problems, which in turn depends on good situation awareness and metacognitive skill.

5.5. Conclusions: The Future of Aviation Decision-Making

The jobs of pilots and air traffic controllers are constantly evolving. With modern equipment on the flight deck, pilots have more information at their disposal. Designing information displays to support good situation awareness and fast, accurate problem diagnosis is a theme of current research and development efforts. Providing information on risks is more problematic. New systems may be able to critique proposed plans for flaws—essentially, an intelligent automated metacognitive aid. Advances in technology will be accompanied by changes in roles and responsibilities in the not-too-distant future. The question will become how to prepare crews and controllers, with their deep knowledge and adaptability, but also with their vulnerabilities, to manage such a system. Mutual trust, respect, and a positive crew climate will continue to be the foundation for effective crew decision making in future automated systems.

Acknowledgments

The author’s research was supported by the National Aeronautical and Space Administration (NASA) Aviation Safety Program and by the Federal Aviation Administration (FAA). The opinions expressed in this chapter are the author’s and do not represent official views of any federal agency.

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