



Flight Crew Decision Making: Now and NextGen
Decision Making Capabilities and Limitations, Topic 12-04

Kathleen Mosier, Ph.D., Co-Investigator
San Francisco State University

Ute Fischer, Ph.D., Co-Investigator
Georgia Institute of Technology

Judith Orasanu, Ph.D., Principal Investigator
NASA Ames Research Center

Interim Report
FAA/NASA NextGen Flight Deck Human Factors Research
Interagency Agreement #DTFAWA-10-X-80005, Annex 9

Submitted to Dr. Tom McCloy
Scientific and Technical Advisor for Human Factors
FAA Human Factors Research and Engineering, ATO-P

March 13, 2011

*POC: Judith Orasanu, NASA Ames Research Center, Mail Stop 262-4, Moffett Field, CA
94035-0001, JORASANU@NASA.GOV, 650-604-3404*

Table of Contents

FLIGHT CREW DECISION MAKING: NOW AND NEXTGEN	1
1 FRONT-END AND BACK-END PROCESSES OF DECISION MAKING	4
1.1 FRONT-END PROCESSES: SITUATION ASSESSMENT AND SITUATION AWARENESS	5
1.2 BACK-END PROCESSES: CHOOSING A COURSE OF ACTION	6
1.2.1 Rule-based decisions.....	7
1.2.2 Multiple-option decisions.....	7
1.2.3 Ill-defined problems.....	8
1.2.3.1 Procedural management	8
1.2.3.2 Creative problem-solving	9
1.2.4 Correspondence and Coherence in Front- and Back-end Processes	9
1.2.4.1 Correspondence	10
1.2.4.2 Coherence	11
1.3 MODELS OF DECISION MAKING.....	11
1.3.1 The Lens Model.....	11
1.3.2 Cognitive Continuum Theory.....	12
1.3.3 Decision Ladders	13
1.3.4 Naturalistic Decision Making (NDM) Models.....	14
1.3.4.1 RPD Framework	14
1.3.4.2 R/M Theory	15
2 WHAT EXPERIENCED PILOTS BRING TO THE DECISION PROCESS: EXPERTISE AND TEAMWORK.....	15
2.1 EXPERTISE.....	15
2.2 TEAMWORK.....	16
2.2.1 Flight Crew Decision Making.....	17
2.2.1.1 Front-end Processes.....	17
2.2.1.2 Back-end Processes	18
2.2.2 Task Management	18
2.2.3 Shared Mental Models	18
2.2.4 Team Communication	19
2.2.4.1 Explicitness.....	19
2.2.4.2 Feedback.....	20
2.2.4.3 Participation Structures.....	20
2.2.4.4 Leader Briefings	20
2.2.4.5 Crew-Oriented Error Correction.....	20
3 WHAT AUTOMATION BRINGS TO THE DECISION PROCESS: DECISION SUPPORT	21
3.1 THE COCKPIT AS HYBRID ECOLOGY	21
3.2 AUTOMATED DECISION AIDS	22
3.3 THE IMPACT OF AUTOMATION ON CREW COMMUNICATION	22
4 CHALLENGES AND IMPEDIMENTS TO DECISION MAKING.....	23
4.1 HOW CAN CREW DECISION MAKING GO WRONG?	23
4.1.1 Defining decision errors in naturalistic contexts.....	23
4.1.2 Challenges to front end processes	24
4.1.3 Challenges to back-end processes	24
4.2 CAUSES OF DECISION ERRORS.....	24
4.2.1 Characteristics of the task environment	25
4.2.1.1 Physical environment	25
4.2.1.1 Time pressure	25
4.2.1.2 Ambiguous or inadequate information.....	26
4.2.1.3 Technological environment	26
4.2.2 Poor Team Communication and Coordination	28
4.2.3 Individual Cognitive Factors	28
4.2.3.1 Salience.....	29

4.2.3.2	Information Integration and the Limitations of Expertise.....	30
4.2.4	<i>Operator State</i>	31
4.2.4.1	Stress and fatigue.....	32
4.2.4.2	Expertise and operator state.....	34
4.3	HUMAN TENDENCY TOWARD HEURISTICS AND BIASES (H&B).....	35
4.3.1	<i>Representativeness</i>	36
4.3.2	<i>Availability</i>	37
4.3.3	<i>Confirmation bias</i>	38
4.3.4	<i>Framing</i>	39
4.3.5	<i>Overconfidence</i>	40
4.3.6	<i>Automation Bias</i>	40
4.4	WHEN DO HEURISTICS WORK?.....	41
4.5	ORGANIZATIONAL PRESSURES: SAFETY CLIMATE AND CULTURE.....	42
5	CREW DECISION MAKING IN NEXTGEN: CHANGES AND CHALLENGES.....	44
5.1	CRITICAL CHANGES TO CURRENT OPERATIONS.....	44
5.1.1	<i>Changes in roles and responsibilities</i>	44
5.1.2	<i>Proliferation of automation</i>	44
5.1.3	<i>Datalink communication</i>	45
5.2	DECISION-MAKING CHALLENGES IN NEXTGEN.....	46
5.2.1	<i>Information overload</i>	46
5.2.2	<i>Development of new expertise</i>	46
5.2.3	<i>Overreliance on automation</i>	46
5.2.4	<i>Non-vigilance and fatigue</i>	46
5.2.5	<i>Erosion of skills</i>	46
	ACKNOWLEDGEMENTS.....	47
	REFERENCES.....	47

Flight Crew Decision Making: Now and NextGen

Decision making in aviation cannot be examined in a vacuum. It must be seen in context—contextual variables both create the need to make a decision and impact people’s judgment and decision processes; their decisions, in turn, impact the context. Probably the most salient characteristic of NextGen operations is that the flight context will be even more highly automated than it is now, requiring decisions in a dynamic and continually changing environment. Automation and technology impact the decision context by creating ecologies that are hybrid—a combination of naturalistic and electronic elements. Each side of the ecology lends itself to particular strategies and is susceptible to particular pitfalls. Technology provides advantages such as enhanced monitoring and data processing capabilities; more precise measurement, calculation and navigation; and high reliability of system diagnoses. However, technological environments also enable flawed judgment and decision processes such as over-reliance and complacency, misuse or heuristic use of automation, and blind compliance (Mosier & Skitka, 1996; Parasuraman & Riley, 1997; Sarter & Schroeder, 2001). Rapid decision making on the naturalistic side of the ecology is enabled by pilot experience and expertise, but may be susceptible to human tendencies to employ heuristic shortcuts in decision making, as well as operator state variables such as fatigue, stress, or affect.

Decisions in NextGen will also entail multiple players, and possibly conflicting individual and team goals must be taken into account. Technology enables collaboration among stakeholders in varied locations – in airline operations centers, in air traffic operations centers, and on the flightdeck. Technology also heightens the need for common assessments or mental models of situations and collaboration during judgment and decision making. Although teams may not be co-located, their judgment and decision processes require shared knowledge and cognition, as well as efficient communication.

In Section 1 of this report we present the components of the decision-making process, and some of the most important and relevant models of decision making. Sections 2 and 3 describe what experienced crews and automation bring to the decision process. Section 4 discusses challenges and impediments to decision making, and Section 5 discusses challenges for decision making in NextGen operations, with emphases on what is new or different.

1 Front-end and Back-end Processes of Decision Making

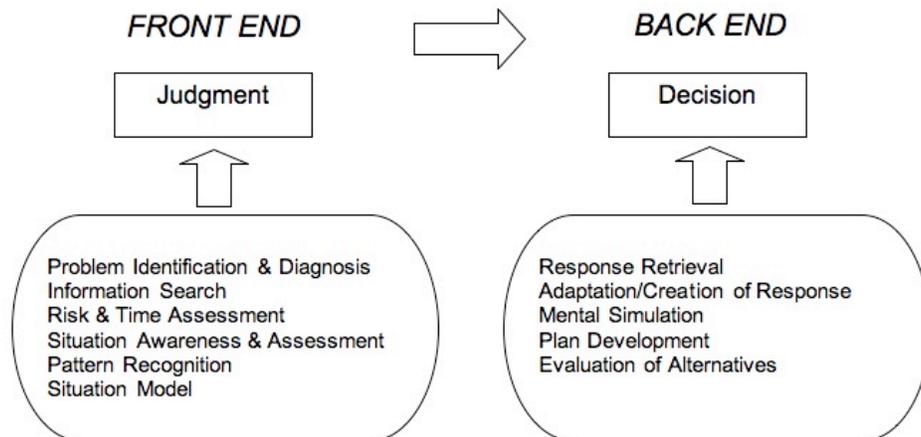
Mosier and Fischer (2010) offered the terms *front end* and *back end* to delineate two phases of decision making. Crew decision making is triggered by some cue, pattern of cues or event that crew members perceive as inconsistent with their current situation understanding or their task goals. As shown in Figure 1, front-end cognitive processes not only concern problem identification but also include information search, problem diagnosis, risk assessment and the evaluation of time constraints (C.f., Orasanu, 2010; Orasanu & Fischer, 1997). Front-end processes make up what is most often referred to as the judgment phase of decision making. Related terms are diagnosis, situation assessment and awareness, situation model, and pattern recognition. Front-end processes result in a judgment, which may be a rather straightforward evaluation of the initial cue (as when flight crews judge their fuel remaining as insufficient to reach their destination airport), or it may involve a complex mental representation (as when a pilot integrates status indicators from various systems to diagnosis a problem). An individual’s

judgment is not always based on deliberation; for instance, as we will discuss later, pattern recognition is an intuitive, rather than an analytical process. However, once operators make a judgment about a problem, their judgment will trigger decision processes.

Decision processes form the back end of decision making, concern the response to the problem, and culminate in a final decision. Back-end processes may involve retrieving an appropriate course of action from memory, locating a prescribed response in the appropriate manual, adapting a known response to the specific demands of the current situation, mentally simulating a possible response, planning a sequence of actions, or evaluating alternatives. A pilot may run a procedure through his or her mind, envisioning the outcome of a particular choice or action - for example testing the accuracy of his/her judgment of height and distance by imagining him/herself making the turn to final at a particular spot and completing the landing.

Figure 1. Components of the decision-making process. Ovals signify cognitive processes; rectangles refer to process outcomes. From Mosier & Fischer, 2010.

The distinction between front-end and back-end processes is not merely of theoretical



significance; rather it is important because aviation human factors applications such as system design or training must be approached very differently depending on the target phase. For example, decision support geared toward front-end processes will facilitate diagnoses, situation assessment and situation awareness; systems geared toward back-end processes will focus on aiding correct option selection or choice of actions.

1.1 **Front-end Processes: Situation Assessment and Situation Awareness**

Situation awareness (SA) is a concept that originated in aviation psychology to characterize critical components of pilots' understanding of their current flight situation but has since been widely adopted by human factors researchers (Durso & Gronlund, 1999). Its appeal stems largely from the fact that it helps explain pilot, or more generally, operator behavior; that is, how operators understand the physical and technological environments in which they work is believed to drive the actions they will take. Prevalent approaches to situation awareness seek to identify underlying cognitive processes and representations, and view situation awareness as separate from decision making and performance (Endsley, 2000); however, some (e.g., Klein, 2000) have emphasized the connection between practitioners' situation understanding and the actions a given situation affords them.

Endsley (1995a,b, 1999, 2000, 2004) characterizes situation awareness in terms of three ascending levels of understanding: "the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (Endsley, 1988, quoted in Endsley, 2000, p. 5). These levels are defined as states of knowledge, are assumed to involve conscious thought and seen as distinct from the cognitive processes on which they are based. Endsley (2000) refers to these underlying processes as situation assessment. In contrast, Durso and collaborators (Durso, Rawson, & Giroto, 2007; Durso & Sethumadhavan, 2008) conceive of situation awareness as comprehension of dynamic situations, which, analogous to text comprehension, relies on several, integrated cognitive processes each targeting different kinds of information. Surface level processes concern the perception and mental representation of elements in the environment, as well as their spatial or temporal relationships. Interpretive processes integrate individual elements in the environment into a coherent scene, creating an event-based representation. Representational processes operate on scenes and relate them to domain knowledge to produce an information-rich and highly structured situation model. The situation model enables operators to infer causes of events and to predict future developments. Both models assume that situation awareness depends on data-driven processes (e.g., pilot notices an engine warning light) as well as knowledge-driven processes (e.g., pilot searches for specific information or evaluates significance of cues), and both provide for the classification of errors in situation awareness, dependent on the stage (in Endsley's model), or the specific process (in the model by Durso et al.) in which the break down occurs.

Meta-cognition likely plays an important role in situation awareness; however, how meta-cognitive processes contribute to practitioners' situation comprehension is insufficiently researched (Durso, et al., 2007). By meta-cognition we mean practitioners' awareness of how well or poorly they understand a given situation and their ability to meet emerging demands. For instance, Orasanu and Fischer (1997) observed that pilots frequently engaged in diagnostic actions to obtain additional information about a problem situation and re-allocated task assignments— behaviors that suggest they were aware of the inadequacy of their situation comprehension and the associated workload.

1.2 Back-End Processes: Choosing a Course of Action

After the problem is defined and 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 constrained by the context. What constitutes an appropriate course of action depends on the affordances and constraints of the situation. Sometimes a single response is prescribed in company manuals or procedures. At other times, multiple options exist from which one is 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 and achieve desired goals, the decision-maker must be aware of what constitutes a situationally appropriate process.

1.2.1 Rule-based decisions

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

In many high-risk time pressured situations, such as an engine stall, rapid decompression, or smoke in the cockpit, crew action is prescribed in company operations manuals or FAA guidelines. These situations are deemed to be sufficiently consequential that procedures are specified in order to reduce the crew's need to invent a solution while operating under stress and time pressure. Once cues are recognized as meeting specified conditions, a prescribed action is applied. Go-No Go decisions are a subset of rule-based decisions. These include decisions to reject a takeoff, to do a missed approach, or to terminate a landing. Multiple cue sets may trigger the 'no-go' decision. For example, a missed approach may be initiated by the crew's inability to see the runway at decision height, by air or ground traffic, autopilot disengagement, or an unstabilized approach.

The crew's primary determination in all rule-based decisions is whether any circumstances exist that suggest the pre-defined response should not be implemented. Risk assessment plays into this decision, particularly when ground speed or altitude approach a decision threshold. Certain conditions, like a wet runway or system malfunction that result in poor braking, may complicate the decision.

Most rule-based decisions in aviation are codified in FAA regulations or company operations manuals. When decisions are not codified or proceduralized, the basis for condition-action pairings is the decision-maker's experience, which builds on deep domain knowledge (e.g., fire fighting). Klein (1989, 1998) found that experienced decision-makers recognize a cue configuration as signaling a particular type of problem; this cue pattern retrieves an action response that proved success in prior experience with similar problems, yielding Klein's 'recognition-primed decisions' (1989, 1993). Once a response option is retrieved, it is evaluated by mentally simulating its consequences to determine whether it 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.

1.2.2 Multiple-option decisions

Some flight decisions involve choice from among alternatives present in the situation. 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 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; Mosier-O'Neill, 1989; Orasanu, 1993, 2010) 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 minimal cognitive work (Fiske & Taylor, 1991).

Options often are eliminated on the basis of one feature, such as weather, and are out of the running thereafter, unless no suitable option 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, the crew's goals and perceived risks. Usually, the most safety-critical constraint prevails. However, organizational policy also plays an important role. For example, 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.

1.2.3 Ill-defined problems

Perhaps the most challenging decisions involve ill-defined problems: Ambiguous or conflicting cues make it impossible to define the problem; no prescribed response option is available; and/or response outcomes are uncertain. Two strategies typically are used to cope with this type of situation: manage the situation as though it is an emergency without clearly defining the problem (procedural management; Orasanu, Fischer & Tarrrell, 1993), or develop a tentative problem definition and then generate a novel solution to achieve one's goals because no prescribed procedure exists (creative problem solving) (Lipshitz & Strauss, 1997).

1.2.3.1 Procedural management

Certain cues are ominous but leave the crew without a clear diagnosis of the underlying problem, usually because no engineered cues describe the condition. These include various noises, thumps, vibrations, rumblings, pressure changes, or aircraft control problems. If the crew perceives the risk to be high, as would likely be the case with smoke, loss of pressure, an acrid smell, an explosion, or loss of control, procedures typically are initiated to 'safe' the situation, and often to land immediately. Little time is devoted to diagnosing the problem. 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 rule-based situations, with the condition broadly labeled as 'emergency landing.' If the risk is not defined as significant and imminent, then additional energy may be devoted to situation diagnosis.

1.2.3.2 Creative problem-solving

Perhaps the most difficult types of decisions are those requiring creative problem solving. These cases tend to be low-frequency events; neither aircraft designers nor operators imagined such a situation would arise, so no procedures were designed to cope with it.

Diagnosis typically involves causal reasoning, which is reasoning backward from effects to cause, as well as hypothesis generation and testing. 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 ill-defined 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. After considerable diagnostic effort, the captain determined that the two outboard engines were still running, but no flight controls were operative. Knowing this, the crew reasoned they could use asymmetrical engine thrust to turn the plane and power level to control the altitude, which they used to bring the aircraft to a semi-controlled landing.

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 (Orasanu, Fischer, & Tarrell, 1993). 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. The cause of oxygen depletion could not be determined nor could the problem be fixed. Regulations require emergency oxygen in case of rapid decompression. 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 in case of rerouting around bad weather.

This above effort to classify decisions in terms of situational demands and affordances is a step toward understanding what makes decisions difficult, cognitive requirements and vulnerabilities, and how NextGen automation may influence decision processes.

1.2.4 Correspondence and Coherence in Front- and Back-end Processes

Two standards exist for examining the goodness of decision-making processes: correspondence and coherence. These terms have been variously used to describe perspectives of truth, strategies, and goals of decision making. Correspondence refers to the criterion of empirical accuracy, and coherence refers to the criteria of rationality and consistency (Hammond, 1996, 1999, 2000). Evaluating the outcome of decision processes (back end: decision makers' actual decisions) is relatively straightforward because decisions are overt and available. The ultimate test of a specific decision outcome is typically its correspondence, or empirical accuracy, with respect to predictions or goals (i.e., Did the decision/action 'work?'). Coherence of back-end processes can be evaluated by examining whether outcomes reflect consistency and rationality across decision situations.

Evaluating correspondence and coherence of the front end—judgment, diagnosis, situation assessment and awareness—is trickier because front-end processes are often covert and not easily available. Moreover, decision makers’ problem understanding or situation models and consequently their resulting judgments entail subjective components—risk is a subjective assessment (Yates & Stone, 1992)—or task conditions may be consistent with different interpretations (Fischer, Orasanu, & Davison, 2003; Fischer, Orasanu & Wich, 1995). Nonetheless, both correspondence and coherence are important in the front end, and different tactics have been employed to measure each criterion.

1.2.4.1 Correspondence

Correspondence, or empirical accuracy, is a function of how well an individual uses multiple and often fallible (i.e., probabilistic) indicators to make judgments and decisions in the world. A pilot, for example, strives for correspondence when checking cues to judge height and distance from a runway and deciding when to turn for final approach. These processes are evaluated according to how well they represent, predict, or explain objective reality. In theories such as Multi-Attribute Utility Analysis (Keeney & Raiffa, 1976) or Brunswik’s Lens Model (Brunswik, 1943, 1955; Hammond & Stewart, 2001), each cue’s weight should derive from its ecological validity—that is, its value when predicting the criterion. According to these linear-additive models, the most appropriate weighting scheme will result in the most correspondent judgments.

Features of the environment and the quality of the cues utilized will impact the accuracy of both front-end and back-end processes. Cues that are highly ecologically valid, are concrete and/or can be perceived clearly will facilitate accurate judgments and correct decisions. Cues that are ambiguous, or are murkier because they are not as concrete in nature or are obscured by factors in the environment, will hinder accurate judgments and adversely impact decisions (Mosier, 2002). Sometimes, accurate decisions may entail creative processes when no known solution fits the perceived situation or diagnosis.

Although correspondence is most obvious as a criterion for the outcome (back-end) of decision making—clearly, accurate decisions are the goal—it is also a criterion for underlying front-end processes. It is generally assumed that operators need to have “good” situation awareness to successfully perform their task; however, its specification is less obvious, if not futile as some have argued (e.g., Dekker & Lützhöft, 2004). Elements that constitute a situation are domain-dependent and thus characterizations of situation awareness need to account for context-specificity. On the other hand, descriptions that are closely tied to specific instances have rather limited scientific value. Moreover, situation awareness is determined by practitioners’ goals and reflects a subjective interpretation rather than an objective rendition of a situation. As a solution, Endsley (1999) suggests that situation awareness be characterized in terms of domain-specific constants. For the aviation environment she identifies geographical situation awareness which includes elements such as location of own and other aircraft, or terrain features; spatial/temporal situation awareness which refers to elements such as attitude, altitude, or current and projected flight path; system SA which includes items such as system status, functioning and settings; environmental SA which concerns items such as current or projected weather conditions; and lastly, tactical SA which among other things refers to the tactical status and capabilities of own vs. other aircraft. Similarly, Wickens (2002) posits three aspects of SA in aviation: spatial awareness, system awareness, and task awareness.

1.2.4.2 Coherence

The criterion of coherence, or rationality and consistency, is most often applied to front-end processes, and is more difficult to measure than correspondence. Coherence has traditionally been evaluated against the standard of mathematical models, and is expected to follow Bayesian (1958) laws of probability. In traditional decision-making research, the situation is typically set up so that one choice is more consistent with laws of probability than another (for example, an event that involves two conjoint circumstances is always less likely than an event with no conjoint circumstance) and coherence in judgment is inferred from the choice made. This concept is central in the research on heuristics and biases: the use of heuristics is viewed as a non-coherent strategy that leads to biased judgments and decisions.

In high-tech aviation cockpits, deterministic information rather than probabilistic cues provides the basis for front-end processes, and both coherence and accuracy depend upon decision makers using all relevant information logically and consistently. A pilot seeks coherence when configuring the aircraft for landing, ensuring that all system parameters displayed in the cockpit are appropriately set. What is important for coherence in automated environments is completeness and consistency of the judgment, diagnostic, or situation assessment process, especially in cases where empirical accuracy is not known or not easily accessible (Hammond, 1996; 2000; 2007; Mosier, 2002; 2009).

1.3 Models of Decision Making

The broad goal of many decision models is to determine what front-end and back-end processes are associated with the best or most accurate decisions. One common methodology is *policy capturing*, in which a series of judgments of the same variable is made on the basis of sets of manipulated cues, and individuals' judgment strategies can then be mathematically or statistically modeled. Camasso and Jagannathan (2001), for example, asked private pilots to make a series of choices between pairs of airports for their base of flying activities, and then used policy capturing to determine what variables or cues were weighted most heavily in their choices. The assumption in policy capturing is that a linear-additive model that relates cues to criteria as determined by linear regression will provide the best assessment of judgment performance. Beta weights associated with cues indicate their importance, and the most successful judges give the highest weights to the best predictor cues (Kirlik & Bertel, 2009).

1.3.1 The Lens Model

Perhaps the best known policy-capturing model is Brunswik's Lens Model (1943; 1956). According to this model, people base their judgments of other individuals or objects on probabilistic cues or attributes in the environment (Hammond, 1996; Hammond & Stewart, 2001). Examinations of individual judgments must take into account the role of the environment and the ecological validity of cues being used (i.e., the degree of relatedness between cues and criterion). Moreover, to understand the factors that impact judgment one can examine systematically not only variations in context, but also variations in decision makers.

Recently, some human factors researchers have relied on the Brunswikian framework and the Lens Model to perform judgment analyses in the high-technology aviation environments - to compare, for example, judgments of *technology as decision maker* with those of human decision makers in a task environment; to explore human judgment with *technology as cue* within an array of cues; or to capture judgment strategies with *technology as environment*, or

contrast them with judgments in *non-technological* environments. Bisantz and Pritchett (2003), for example, related *technology as decision maker* to human judgments. They used the Lens Model to distinguish participant judgment strategies and outcomes in a simulated aircraft conflict detection task across a variety of conditions, and compared them with those generated by several automated collision alert systems. In a variant of this work, Bass and Pritchett (2002) investigated the human-automated judgment system interaction, using an adapted Lens Model to characterize the interaction and resultant judgments in an air traffic conflict prediction task.

Other explorations have looked at *technology as cue*, including investigations of presentation mode or display design of automated decision aids, or the impact of technological cues on judgment strategies. Research on automation over-reliance and automation bias, for example, has demonstrated that high-tech sources of information are often weighted much more heavily than other cues in the diagnosis process (e.g., Mosier et al., 1998). Effects of display variations were examined by Strauss and Kirlik (2006), who demonstrated that the Lens Model was effective for detecting and diagnosing differences in judgment performance associated with display design in submarines.

The Lens Model has proven to be a valuable research tool to explore decision making in dynamic environments such as aviation, and may be seen as a complementary approach to naturalistic decision making (NDM) models described later in this section. Complexities of the environment as well as features of the cues utilized such as ‘goodness’ or relevance, will impact the accuracy of judgments. Situational factors are critical in examinations of dynamic decision-making environments, as is taking into account the impact that changes in these factors can have on judgment processes and outcomes. There is also some evidence that characteristics of the decision maker will affect judgments in dynamic environments. Domain experts, for example, exhibit tactics that are different from those of novices, and are more likely than novices to understand relationships among cues, to evaluate the validity of cues accurately, and to use cues effectively in making their judgments (e.g., Zsombok & Klein, 1997).

1.3.2 Cognitive Continuum Theory

The notion of a cognitive continuum from intuition → analysis was developed by Hammond (e.g., 1993; 1996; 2000). *Analysis* refers to a "step-by-step, conscious, logically defensible process," whereas *intuition* typically describes "the opposite - a cognitive process that somehow produces an answer, solution, or idea without the use of a conscious, logically defensible, step-by-step process" (Hammond, 1996, p. 60). Hammond refers to intuition and analysis as the "easy" and "hard" ways to achieve coherence and correspondence.

According to cognitive continuum theory, intuition and analysis represent the endpoints on a continuum of cognitive activity. Judgments vary in the extent to which they are based on intuitive or analytical processes, or some combination of both. At the approximate center, for example, is *quasi rationality*, sometimes referred to as common sense, which involves components of intuition as well as analysis. During the judgment process, individuals may move along this continuum, oscillating between intuition and analysis - or stopping at points on the continuum (Hamm, 1988). Pilots, for example, may use intuition when gauging weather from clouds ahead, switch to analysis to read and interpret printed weather data, and utilize some combination of the two to judge the safest path, or decide whether to continue on or turn back.

Intuition and analysis differ on several cognitive properties. Intuition is characterized by rapid data processing, with low cognitive control and little to no conscious awareness of processes. It is imprecise but robust, in that accuracy can be achieved despite the inappropriate use of a weighted average organizing principle, and errors tend to be normally distributed. People who make judgments intuitively typically exhibit high confidence in their answer, although they may not be as confident in the method by which it was derived. In contrast, analysis demands high cognitive control and conscious awareness. It requires task-specific organizing principles, and slow processing of data. Analysis is precise but brittle, in that errors occur less often but are likely to be large when they do occur. People who make judgments analytically typically exhibit high confidence in their method, but may not be as confident about their answer (see Hammond, McClelland, & Mumpower, 1980; Hammond et al., 1997).

Processes described by any point on the continuum may be used to achieve correspondence or coherence. In the aviation context, novice pilots may *analytically* strive for correspondence – accuracy – by using a combination of cues, rules and computations to figure out when to start a descent for landing. Pilots also learn to use *intuitive*, pattern-matching processes to assess cues and judge situations. As they gain more experience, the correspondence process becomes more recognitional, and their *intuitive* assessment of whether the situation “looks right” to start down becomes increasingly effective. In the naturalistic environment, a pilot’s correspondence competence – that is, the ability to utilize probabilistic cues in the environment to assess situations and predict outcomes - increases with expertise. Expert pilots are able to quickly recognize a situation, and may be able to use intuitive processes under conditions that would demand analysis of a novice.

Specific task properties are conducive to, or induce, specific modes of cognition. Task environments that contain a large number of cues displayed simultaneously and briefly, high redundancy among cues, perceptual measurement, and a low ability to attain certainty in the task will induce intuitive cognition. In contrast, task environments that contain a small number of cues displayed sequentially and at length, low redundancy among cues, and the ability to attain certainty in the task will be conducive to analytical cognition. The precise location of cognitive activity along the continuum, that is, the amount of intuition and/or analysis used to complete the task, will depend on which task properties are present, and to what extent (number and amount; Hammond, Hamm, Grassia, & Pearson, 1997).

1.3.3 Decision Ladders

The *decision ladder* (Rasmussen, 1976; Vicente, 1999; Vicente & Pawlak, 1994) is a control task model that incorporates front and back-end processes of decision making as legs of a ladder. (See also Naikar, Moylan, and Pearce, 2006, for an annotated model). Boxes represent stages of information-processing activities, and ovals indicate the resultant knowledge. On the left side of the ladder are the front-end processes: the perception of a state of affairs that is unsatisfactory or threatening, information gathering, situation assessment and diagnosis. At the top of the ladder are the back-end processes – prediction of consequences and evaluation of options--and the descending right leg represents the planning and execution of the action.

The decision ladder model has several unique facets that enable it to capture differences in operator decision processes. Importantly, it incorporates the ability to take shortcuts, or ‘leaps’ between knowledge points, as when an experienced pilot skips from the point of system state diagnosis to knowledge of the corrective procedure (Bisantz et al., 2003). Additionally, the

model recognizes that decision activities can start on the right as well as the left side of the ladder—as when an expert begins with identification of the target state—and can flow in either a left-to-right or right-to-left sequence (Naikar et al., 2006). These features acknowledge that decision processes are likely to be different depending on the domain expertise of the decision maker, a notion that is also a primary component of the Naturalistic Decision Making models discussed below.

1.3.4 Naturalistic Decision Making (NDM) Models

In the last two decades, models broadly classified under the framework of NDM have been used to explore decision making in diverse operational settings, examining for instance how offshore installation managers, fire ground commanders, military platoon leaders, Army tactical battlefield leaders, design engineers, or commercial airline pilots make decisions (Cohen, 1993; Cohen, Adelman, Tolcott, Bresnick, & Marvin, 1993; Flin, Slaven, & Stewart, 1996; Klein, 1989; Klein, Calderwood, & Clinton-Cirocco, 1986; Mosier & Chidester, 1991; Orasanu & Fischer, 1997). This work describes the process of making decisions in situations involving poorly structured problems, uncertain and dynamic environments, shifting or competing goals, action feedback loops, time pressure, and multiple players (Orasanu & Connolly, 1993). These situations often call for immediate action, with potentially dire consequences for bad choices.

Characteristics of NDM models include: 1) process orientation, emphasizing the cognitive processes of proficient decision makers—what information they use and how they use it; 2) situation-action matching decision rules—decision making by proficient decision makers is a matter of sequential option evaluation (if indeed more than one option is evaluated), and the decision is made in a pattern-matching process rather than a choice; 3) context-bound informal modeling of decision processes—models are applied and knowledge is domain specific; and 4) empirical-based prescription—prescriptions for decision making are derived from descriptive models of expert performance (Lipshitz, Klein, Orasanu, & Salas, 2001)

The Recognition-Primed Decision Making (RPD) framework (Klein, 1993a; 2008) and Recognition/Metacognition Theory (R/M) framework (Cohen, Freeman, & Wolf, 1996; Cohen, Freeman, & Thompson, 1997; Cohen, 2011) have highlighted the importance of front-end processes—accurate situation assessment in particular—in expert decision making. Options are generated and evaluated sequentially and may come from prescribed responses (such as procedures), from the retrieval of similar situations from memory, or from the invention of a novel course of action (Orasanu & Fischer, 1997; Serfaty et al., 1997). They are tested sequentially via back-end processes such as *mental simulation* (Klein, 1993 a, b) or *matching*, in which the expert matches a plan of action against his or her model of the situation and visualizes its effectiveness (e.g., Serfaty et al., 1997).

1.3.4.1 RPD Framework

The RPD model (Klein, 1989, 1993a,b) outlines perhaps the most often cited framework of NDM and is defined by three core aspects: the quality of the decision maker's situation assessment, his or her level of experience/expertise, and the use of recognitional rather than analytical decision processes. Situation assessment is at the heart of the RPD model and is highly dependent on the individual's level of experience/expertise. The degree to which flight crews can recognize that a situation is similar to one previously encountered comes into play. In familiar situations, pilots expect patterns of certain, relevant cues. The identification of these cues confirms their

expectation, and triggers recall of solutions that have been successful in the past, thereby facilitating pilots' response selection in the current problem situation.

1.3.4.2 R/M Theory

Recent iterations of the recognitional model acknowledge that analytical processes may be involved when situations are not familiar or facets of the situation do not meet expectancies. Situations may call for analytic or constructive thought processes such as sense making, or coming to an understanding of the situation by connecting situational elements into a causal and/or temporal order, placing elements into frameworks, accounting for unexpected or inconsistent elements, and planning and replanning (Klein, 2008; Klein et al., 2003; Weick, 1995). Cohen's R/M model in particular focuses on these types of situations, in which recognition does not work, and instead require the decision maker to construct causal models or stories. These expand and change as experts collect and synthesize data. The R/M model's STEP procedure (construct a Story, Test its plausibility, Evaluate the goodness of the assessment through critical questioning, Plan for the possibility of error; Cohen et al., 1996) describes how decision makers may cope with uncertainty.

Metacognition, or the process of monitoring and controlling one's cognitive processing, as well as the metarecognitional skills of critiquing and correcting, are used to verify the correctness of diagnosis or situation assessment. Experts have been shown to be more likely than novices to recheck and confirm or revise their initial assessments (e.g., Chi, Glaser, & Rees, 1982; Khoo & Mosier, 2008; Patel & Groen, 1991), and according to the R/M model, this process continues until the situation model that has been created is satisfactory, or until the potential benefits of further processing are outweighed by the costs (Cohen et al., 1996; 1997). Metacognitional monitoring is also a facet of back-end processes, for instance when battle commanders continuously evaluate how their selected course of action may impact the situation and whether it may need to be modified (Serfaty et al., 1997).

2 What Experienced Pilots Bring to the Decision Process: Expertise and Teamwork

2.1 Expertise

Expertise impacts the decision process in several ways. First, experienced decision makers exhibit high competence within their domain and have accumulated a vast repertoire of instances or cases they can draw on (e.g., Chi, Feltovich, & Glaser, 1981; Chi, Glaser, & Farr, 1988; Klein, 1993a; Patel & Groen, 1991; Simon & Chase, 1973). Charness and Tuffiash (2008) note that experts' superior performance in domains such as aviation is directly dependent on their domain-specific knowledge, and that this knowledge enables experts to anticipate future actions and prepare for them more efficiently.

Second, experts see and process information differently than novices. For instance, a card-sorting study by Fischer, Davison, and Orasanu (2003) revealed that commercial pilots' understanding of safety risk was more complex than the risk concept of general aviation (GA) pilots. Commercial pilots' risk perception took account of the dynamic nature of aviation incidents. They were sensitive to the timeline of a threat and distinguished between threats that are imminent, requiring a quick response, and those that loom in the distance, and thus leave some room to maneuver. A second component of commercial pilots' risk concept was the

degree to which a threat is controllable. GA pilots, in contrast, showed a more static understanding of risk. Their risk assessment was predominantly a function of the severity of a threat analogous to the dread factor observed in studies of the general public's understanding of risk (Slovic, 1987).

Importantly, for decision making in naturalistic environments experts are able to quickly identify the most ecologically valid cues, that is, the subset of information most critical to accurate situation assessment and to match these cues against patterns in their experience base. Experienced pilots, for example, match the shape, color and size of clouds with patterns in memory to determine whether they should fly through them or around them. The ability to use pattern-matching processes in naturalistic environments enables quick diagnosis and decision making as experts are able to comprehend quickly what may be at the core of a problem and what actions should be taken (Cellier, Eyrolle, & Marine, 1997; Orasanu & Connolly, 1993). This is a critical factor in time-constrained situations.

Experts are sensitive to constantly changing values of information and adapt their mental models accordingly (Waag & Bell, 1997). Often, decisions are made incrementally and iteratively as decision makers use feedback from the environment to adjust their actions and are able to change course in the middle of a situation when a decision is not working effectively (Connolly, 1988; Lipshitz, 1993). Mosier and Chidester (1991), for example, found that the most successful flight crews demonstrated an iterative process in solving an oil pressure problem. They made preliminary, modifiable decisions and continued to gather information and monitor results of their actions to refine their diagnoses (see Fischer, Orasanu & Montalvo, 1993; Orasanu & Connolly, 1993, for other examples). Situation assessment of experts is typically characterized by action/feedback loops, as they use an iterative process to incorporate changes that result from incremental decisions.

Experts also employ strategies that enable them to cope with ambiguity, dynamic conditions and time pressure. They are proactive, anticipate potential failures, risks or conflicts, and prepare for them. They are aware of time constraints and know how to 'buy time.' For instance, pilots may request a holding pattern to gather additional decision-relevant information (Orasanu, 1994). To manage time wisely, experts anticipate developments, make contingency plans, prioritize tasks, and use low-workload periods to prepare for upcoming events (Fischer, Orasanu, & Montalvo, 1993; Orasanu, 1994).

2.2 Teamwork

Aviation decision making is essentially a team process (even in a single pilot aircraft). A team is typically defined as a group whose members have specialized expertise along with their roles and responsibilities; members' behaviors are interdependent; and communication is essential for coordinated action toward a common valued goal (Dyer, 1984). While the primary team of concern in this report is the flight crew of multi-crew aircraft, other aviation teams include the flight crew interacting with ATC and the flight crew interacting with the airline's operations center (AOC). To the extent that automation is becoming more 'intelligent' and

‘adaptive,’ we may also consider the crew and flight deck automation as a team (Christoffersen & Woods, 2002; Prinzel, 2003).¹

Members of a flight crew are co-located, which means they share an environment, including overlapping visual fields, and broad communication bandwidth, including face-to-face communication, voice inflections, facial expressions, and gestures. While authority and status differences exist, crewmembers also share sufficient knowledge and training to alternate roles of pilot flying and pilot not-flying. Being members of a co-located team enhances their cognitive resources relative to a solo decision maker. Greater cognitive capacity is available for monitoring the environment, processing information, communicating with the outside world, managing systems, preventing and correcting errors, and making decisions. These enhanced cognitive resources help to overcome the cognitive limitations associated with individual stress, fatigue, situation complexity and workload.

Compared to flight crews, teams involving ATC, AOCs and other ground-based resources such as maintenance are distributed geographically. All voice communication between air and ground is mediated, and data sharing is frequently computer based. Being in different environments means the members lack shared access to environmental cues or operator state knowledge. Perhaps most important are the differences between distributed team members in their underlying knowledge, information sources, organization goals, roles and responsibilities. These differences may be the basis for misunderstanding, conflicts, or alternative evaluations of risk, as demonstrated in flight crew-ATC disconnects by Bearman, Paletz, Orasanu and Thomas (2010). While all are concerned with overall system safety, local tactical goals may differ: controllers are concerned with keeping aircraft separated, maintaining the system flow, and managing their workload; while flight crew are concerned with getting their passengers to their destinations on time, with a smooth ride. Given their common business goals, the flight crew may be more closely aligned with their AOC than with ATC.

2.2.1 Flight Crew Decision Making

Given that being a member of a team enhances available cognitive resources, how is this enhancement manifest in aviation decision making relative to solo decision making?

2.2.1.1 Front-end Processes

First, situation monitoring is enhanced in a team context, increasing ability to identify situations that require a decision to be made. This is particularly important in high-workload situations, given the risks associated with incorrect situation assessment. For example, the crash of a B-737 airliner in Kegworth, UK resulted when the crew mistakenly shut down a functional engine before a definitive diagnosis of which engine was having problems (AAIB, 1990). The team’s decision process is driven mainly by how familiar the problem is. If familiar, an appropriate checklist or procedure will be initiated. Team members exchange information to build a shared situation model. They must determine: *Do we need more information to understand the problem? How serious is it? Must some action be taken immediately? How much time do we have to decide?* Information sharing supports development of new plans to meet emergent goals.

¹ Another type of distributed team includes members of airline operations centers (AOC) interacting with air traffic management (ATM), primarily during flight planning and replanning, a topic that will not be addressed in this report.

It is especially important for crews to update their situation models when conditions are changing dynamically (Orasanu, Martin & Davison, 2001).

2.2.1.2 Back-end Processes

Team processes involved in choosing a course of action depend on the complexity of the decision. Once the situation is assessed, if it is a familiar rule-based problem, then an option is generated (often with aid of a checklist or standard procedure) and evaluated by the crew through mental simulation of the outcome. If it is judged to meet the crew's goals and situational constraints, then the option is likely to be accepted and the crew plans how to implement it. If the initial option does not meet the crew's goals or the situation is more complex, then another option is generated or modified and again evaluated. Essential to the evaluation process is recognition of the constraints operating in the situation and the several goals that may be competing. Constraints include available fuel, airport features (e.g., runway length or conditions, terrain, curfews), aircraft capabilities, weather, traffic, and company policies or resources. Competing goals include operational safety, passenger comfort and satisfaction, fuel consumption, and company policy.

In these more complex and ill-structured situations, it is essential for the crew to recognize the levels of uncertainty and downsides associated with various options. Crew members must ask themselves, *What if we are incorrect in our assumptions about the nature of the problem or expectations of likely outcomes? Are we underestimating the risks inherent in a course of action? What if conditions deteriorate? Do we have an alternative plan?* In discussing these issues, the crew may avoid the pitfalls of cognitive tunneling or impulsivity associated with overload or stress (Harrison & Horne, 2000; Keinan, 1987). Several investigators have found that flight crews that engage in higher levels of planning perform better than those who plan less; these performance enhancements have been attributed to building of shared mental models for the situation and how to deal with problems (Orasanu & Fischer, 1992; Stout, Cannon-Bowers, Salas, & Milanovich, 1999).

2.2.2 Task Management

Task management is critical to effective crew decision making: Someone must be assigned to fly the plane, monitor flight deck displays and the external environment, manage automation, communicate with ground and work on problem solutions. Given limited human resources, task priorities must be established, generally the captain's role. In a simulator study of team performance in the face of challenging hydraulic failure problem, crews in which the captain assigned the job of flying to the first officer in order to deal with the problem himself were more successful in coping with the difficulties than those in which the captain continued to fly (Orasanu & Fischer, 1992). Clearly, automation (if functioning properly) may reduce the crew's cognitive load to enable the humans to focus on problem solving and decision making.

2.2.3 Shared Mental Models

Sharing a significant amount of domain knowledge facilitates crew decision making (Orasanu, 2010; Stout, et al., 1999). In complex systems, three types of shared mental models are evident: for *equipment* – its components, their links, how they function, and system limitations; for *tasks* – operational procedures, likely scenarios and contingencies, and task component relationships; and for *teams* – member roles and functions, interdependencies, and information flow (Cannon-Bowers, Salas, & Converse, 1993). These shared models enable team

members to understand behaviors of other members, to predict system developments, to coordinate with increasing efficiency, to anticipate others' information needs, and reduce the communication requirements as team members' models converge over time (Mathieu, Heffner, Goodwin, Salas, & Cannon-Bowers, 2000; Rouse, Cannon-Bowers, & Salas, 1992). Research on communication 'anticipation ratios,' 'implicit coordination,' and team decision making support these assertions (Entin & Serfaty, 1999; Espinosa, Lerch, & Kraut, 2004; Orasanu, 1994).

While much of the research on team knowledge has focused on development of shared knowledge, it is important to ask what and how much knowledge needs to be shared for effective team performance. Clearly, one advantage of a larger team is the greater variety and depth of knowledge it provides relative to a small team. While communication and coordination become more challenging in larger teams (Steiner, 1972), having complementary or compatible knowledge can be a significant advantage (Cooke, Salas, Cannon-Bowers & Stout, 2000). Teams are most critical in domains that are complex and where no single individual can possibly have all the needed knowledge, such as in healthcare (e.g., surgical teams, shock trauma centers), the military, and NASA Mission Control. In these cases team members need the knowledge to perform their own tasks, plus the knowledge to support collaborative decision making. This typically consists of interpositional knowledge, i.e., knowledge of others' tasks and information needs (Cooke, et al., 2000), as well as 'transactive memory,' or knowledge of who knows what (Wegner, 1986). In most environments, completely overlapping models would be both dysfunction and highly unlikely (Klimoski & Mohammed, 1994). Exactly what kind of knowledge needs to be shared and the degree of complementarity for optimal team performance have yet to be determined. Certainly, shared knowledge of the team's goals and intent is essential.

One of the goals of NextGen automation is to enhance information sharing among all partners in the airspace system: the flight deck, airline operations centers, air traffic control and air traffic management centers. However, Bearman and colleagues (2010) have found that differences between flight crews and ATC in their assessments of risk associated with traffic or weather are especially difficult to resolve, and are not eliminated simply by sharing of information or knowledge. Providing common information does not guarantee that it will be interpreted and used similarly by all recipients.

2.2.4 Team Communication

Communication is the primary mechanism for assuring adaptive coordination and collaboration within a team (Kanki, 2010), especially in dynamic, ill-structured situations (Helmreich & Sexton, 2004; Orasanu & Fischer, 1992). The following features characterize the communication of effective teams (Orasanu, Parke, Fischer, & McDonnell, 2009):

2.2.4.1 *Explicitness*

Effective crews use explicit and efficient language to generate shared situation models (Orasanu, 1994), providing more task-critical information than less effective crews, including task goals and team strategies (Bowers, Jentsch, Salas, & Braun, 1998; Orasanu & Fischer, 1992; Sexton & Helmreich, 1999). Moreover, members of effective teams anticipated each other's information needs and volunteered information and assistance (Serfaty, Entin, & Volpe, 1993).

2.2.4.2 Feedback

Communication efficiency is evident in ‘closed-loop’ communication (Kanki, Lozito, & Foushee, 1989) by which team members acknowledge or answer an initiating utterance. Read-backs or active listening that builds on the prior utterance indicate understanding of what was said (Fischer, McDonnell, & Orasanu, 2007).

2.2.4.3 Participation Structures

Certain interaction patterns have also been associated with successful team performance. Fischer et al. (2007) noted that open and inclusive interactions between team members helped their joint performance. Team members contributed equally to the team discussion, and talked freely with each other. However, in teams involving team members of different status, members of lower status may be reluctant to speak up and contribute to their team’s discussion, or their contributions may go unacknowledged or may be rejected (Linde, 1988; Orasanu & Fischer, 1992). The aviation industry’s answer to this problem has been to focus on crew resource management in their pilot training and to encourage consultative leadership in their captains and assertiveness in their first officers (Helmreich & Foushee, 1993).

2.2.4.4 Leader Briefings

Crew briefings are an effective way for leaders to establish crew climate and to define norms for crew interactions and collaboration. Briefings establish common goals, open communication channels, set expectations for safety, and create positive crew climate – not just by talk, but also by modeling (Ginnett, 1987).

2.2.4.5 Crew-Oriented Error Correction

Appropriate error correction strategies enable crews to successfully address problem situations while maintaining a positive crew climate. A risk factor contributing to many aviation accidents is the ‘monitoring and challenging’ error (NTSB, 1994): One crewmember, usually a junior one, is unable to influence the other crewmember (usually the captain) to take action to resolve an important safety issue. Calling attention to an error committed by another crewmember may involve a direct challenge to their status, judgment, or skill. This ‘face threat’ risk to crew cohesion can be mitigated by use of crew obligation statements (e.g., “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”; Fischer & Orasanu, 2000). These strategies all address the problem without disrupting positive team climate. Also, requests 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 those without supporting statements, presumably because the supporting statements contributed to a shared situation model and clarified the rationale behind the request.

3 What Automation Brings to the Decision Process: Decision Support

3.1 The Cockpit as Hybrid Ecology

Automated cockpits contain a complex array of instruments and displays in which information and data are layered and vary according to display mode and flight configuration. Aircraft flight management systems are designed not only to keep the aircraft on course, but also to assume increasing control of “cognitive” flight tasks, such as calculating fuel-efficient routes, navigating, or detecting and diagnosing system malfunctions and abnormalities. NextGen will add even more sophisticated automation to the array. Note that most of these advances are geared toward decision making—making more and better information available, analyzing data, providing alerts, or improving or integrating system and navigation displays.

Electronic systems reduce the ambiguity inherent in naturalistic cues; they process probabilistic cues from the outside environment and display them as highly reliable and accurate information. This has transformed many decision domains into complex, *hybrid* ecologies - deterministic in that much of the uncertainty has been engineered out through technical reliability, but probabilistic in that conditions of the physical and social world (including ill-structured problems, ambiguous cues, time pressure, and rapid changes) interact with and complement conditions in the electronic world (Mosier, 2008, 2009). In a hybrid ecology, cues originating in the external, physical environment must be integrated with information from internal, electronic deterministic systems.

On the naturalistic side of the hybrid ecology, information and cues are absorbed primarily via sensory and kinesthetic mechanisms: the *look* of the weather, the *smell* of smoke, the *feel* of the physical environment. Cues are ambiguous and probabilistic. Accuracy in the front end is central as this enables the selection of a high-quality option. Domain expertise will facilitate these judgments, and enable intuitive pattern matching, or recognition of situations as similar to past experiences (Klein, 1993a).

On the electronic side of the hybrid ecology, information is absorbed by the operator via more analytical cognitive processing: the *parameters* of the system, the *status* of the engines and related systems, the *steps to take* to correct anomalies, the *precise position* of the aircraft. Data and information are specific and highly reliable. Coherence in the front end, in terms of consistent and comprehensive integration of all relevant information for situation assessment, is a central prerequisite for accurate diagnoses and decisions. In the electronic world, domain expertise affords only limited shortcuts, as characteristics inherent in automated systems such as layered data, multiple modes, and opaque functioning may preclude pattern matching, and demand analytical processing from experts as well as novices.

Many task environments include both electronic and naturalistic elements; moreover, decision-making goals and strategies may vary as a function of the particular task at hand. Jacobson and Mosier (2004), for example, noted in an analysis of airline pilots’ incident reports that different decision strategies were mentioned as a function of the context within which a decision event occurred. For example, during traffic problems in good visibility conditions, pilots tended to focus on accuracy goals, reacting to patterns of probabilistic cues for accurate traffic avoidance; however, for incidents involving equipment problems, pilots were more likely

to strive for coherence and consistency, checking and cross-checking indicators to formulate a diagnosis of the situation.

3.2 Automated Decision Aids

The advantages of advanced technology in terms of increased efficiency, data storage and manipulation, for example, are self-evident—automated systems can assimilate more information and process it faster than humans. Some shortcomings, however, must also be considered. Many automated systems are opaque in their operations, and do not enable operators to track their functioning. They cannot take into account context-specific information, and thus may generate faulty recommendations (Gawande & Bates, 2000; Mosier, 2002). Several researchers have documented problems in the use of advanced automated systems, including mode misunderstandings and mode errors, failures to understand automation behavior, confusion or lack of awareness concerning what automated systems are doing and why, and difficulty tracing the functioning or reasoning processes of automated agents (e.g., Billings, 1996; Sarter & Woods, 1994a,b). *Automation surprises*, or situations in which operators are surprised by control actions taken by automated systems (Sarter, Woods, & Billings, 1997), may be the result of non-coherent situation assessment processes—that is, when operators have incomplete or inconsistent information about the situation, or misinterpret or mis-assess data on system states and functioning (Woods & Sarter, 2000). Mode error, or confusion about the active system mode, has resulted in several incidents and accidents in aviation as well as in medicine (e.g., Sarter & Woods, 1994a,b; Sheridan & Thompson, 1994; Woods & Sarter, 2000).

3.3 The Impact of Automation on Crew Communication

The introduction of automation into the cockpit may change the nature of pilots' communications in two important ways. Some (Bowers, Oser, Salas, Cannon-Bowers, 1996; Costley, Johnson, & Lawson, 1989) have observed that automation reduced (either explicit or implicit) crew communication, apparently because pilots could retrieve critical flight information directly from automated systems without input from the other crew member. Similarly, Parke and colleagues (2001) reported that data link clearances were not consistently shared among crew members. This issue may become even more pronounced during NextGen operations, as pilots likely will have to interact with more and increasingly complex automated systems. Easy information access may thus inhibit explicit discussion among crew members, potentially leading to insufficient grounding of task-critical information. To ensure that critical information is shared, airlines mandate that important changes, for instance to the FMS, are announced prior to their execution. However, compliance with this procedure was found to be low (Dekker, 2005).

On the other hand, automation may lead to an increase in pilots' verbal communication. This hypothesis reflects concerns expressed by Wiener (1989) and others (e.g., Sarter, 1995; Segal & Jobe, 1995) who pointed out that automation makes it more difficult for pilots to see and monitor each other's actions, and thus limits pilots' opportunities for non-verbal communication. That is, pilots may compensate for the loss of non-verbal information by talking more. Consistent with this hypothesis, several studies showed an increase in crew communication in automated compared to traditional aircraft (Bowers, Thornton, Braun, Morgan, & Salas, 1998; Veinott & Irwin, 1993), specifically an increase in pilots' task-related communication (Damos, John, & Lyall, 2005). For instance, Veinott and Irwin (1993) observed during a full-mission simulation study that pilots flying an advanced aircraft talked more than their counterparts in the traditional cockpit; in particular question-answer sequences were more prevalent. This finding

suggests that pilots in the automated cockpit were sensitive to changes in their information needs as non-verbal cues disappeared or were ambiguous. Similarly, Parke, Kanki, McCann and Hooey (1999) report that pilots adapted their communication behavior to automation-specific affordances. The availability of navigational aids (Electronic Moving Maps) during taxiing reduced the number of simple information requests but increased the number of traffic-related observations in pilots' discourse. That is, technology that provides pilots with shared visual information may facilitate mutual understanding insofar as this information can be presumed as common ground and need not be explicitly addressed in their communications; in so doing it frees pilots to focus their discussions on those issues that are not yet part of their common ground.

4 Challenges and Impediments to Decision Making

4.1 How Can Crew Decision Making Go Wrong?

4.1.1 Defining decision errors in naturalistic contexts

Defining decision errors in naturalistic contexts, such as aviation, 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.

These difficulties suggest that a viable definition of decision error must take into account both the nature of the decision process and the event outcome. Lipshitz (1997) considers decision errors as "deviations from some standard decision process that increase the likelihood of bad outcomes" (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. To account for the contextual embeddedness of decisions, Woods, Dekker, Cook, Johannesen, and Sarter, (2010) advocate a systems perspective, a view entailing that errors be reframed as a lack of system/person fit. Decision errors are thus the result of normal human activity in response to novel situations. A systems perspective suggests that a more productive approach to identifying decision errors is to examine the interaction between situational features and individual cognitive factors. As Rasmussen (1997) noted, the decision-making field has moved through two phases, from formal prescriptive models of individual cognition to predictive models for evaluating total systems. Current trends emphasize analyses of "behavior shaping features of the environment;" that is, models in terms of "objectives, constraints, options for action, and subjective performance criteria" (p. 73).

Decision errors may arise both within front-end judgment processes and back-end decision processes, entailing both correspondence and coherence failures. That is, pilots may not account

for crucial cues and relevant information, or may misrepresent their relationships and implications resulting in inadequate decisions. Or, they may have an adequate situation understanding; yet, misremember or misapply procedures or fail to consider decision alternatives and their consequences.

4.1.2 Challenges to front end processes

Pilots need to perceive relevant cues in the environment and notice task-critical changes. They also need to remember items in their environment and need to keep track of tasks they have accomplished as well as of those they still have to complete. Both requirements turn on the capacity of working memory (Dismukes, 2010). These perceptual, attentional and memory requirements pose formidable challenges to pilots, especially during off-nominal situations in which time is limited and stakes are high. For instance, attention and memory failures have been identified as underlying causes in many aviation accidents and incidents involving inaccurate situation understanding by flight crews or air traffic controllers. Pilots were found to have overlooked relevant cues, failed to monitor the situation (Jones & Endsley, 1996), misread or misheard information as well as misremembered or forgot information (Dismukes, Berman, & Loukopoulos, 2007; Cushing, 1994; Endsley & Jones, 2000; Jones & Endsley, 1996). Pilots also may not detect task-relevant changes in their environment and consequently fail to update their situation model (Muthard & Wickens, 2002; Sarter & Woods, 1994). Decision errors may also reflect problems with the integration and interpretation of cues (Rodgers, Mogford, & Strauch, 2000), or they may indicate flawed assessments, in particular of safety risk (Fischer, Orasanu, & Davison, 2003; Goh & Wiegmann, 2001; Johnston, 1996; Orasanu, Fischer, Davison, 2004; Wiegmann, Goh, & O'Hare, 2002) and available time (Orasanu & Strauch, 1994).

4.1.3 Challenges to back-end processes

NTSB analyses of accidents highlight the critical role that situation assessment plays in crew decision making. In many cases crews appear to have exhibited poor situation assessment rather than faulty selection of a course of action based on adequate situation assessment (Orasanu, Dismukes, & Fischer, 1993). This finding may be due to the fact that crew decision making is highly proceduralized. That is, the cognitively challenging aspect of crew decision making may be situation assessment; once the situation is understood, the appropriate course of action is frequently prescribed. Nonetheless, back-end processes are not immune to errors. Dismukes and colleagues (2007) note that in some accidents crews did not respond adequately to rare problems (such as a false stick-shaker activation just after rotation) or deviated from explicit guidance or standard operating procedures. Analyses of crew decision making in full mission flight simulations (Fischer, Orasanu, & Montalvo, 1993; Orasanu, 1994) showed inappropriate task shedding (crews focused on one task at the expense of another) and oversimplification (crews treated a choice situation as if it were rule-based or considered fewer options).

4.2 Causes of Decision Errors

Traditional decision research has typically considered the source of decision 'error' to be the limited cognitive capacities or inappropriate strategies used by the decision-maker (Tversky & Kahneman, 1974). However, these approaches did not consider the role of domain expertise in decision making, nor did they typically consider the impact of contextual features on decision processes. The systems approach recommended by Rasmussen (1997) and Reason (1997)

emphasizes the importance of examining contextual factors in order to understand performance errors in operational situations, i.e., to examine ‘error-inducing contexts’ (Orasanu, Martin and Davison, 2001).

4.2.1 Characteristics of the task environment

4.2.1.1 *Physical environment.*

Crew decision making takes place in a dynamically changing environment and is embedded in an overarching task context in which multiple tasks have to be performed simultaneously. Keeping track of changing conditions and concurrent tasks places considerable demands on pilots’ attention and memory and may lead to decision errors (Funk, 1991; Loukopoulos, Dismukes, & Barshi, 2003; Raby & Wickens, 1994). Aviation accident and incident analyses suggest that pilots are prone to decision errors when they are distracted, under stress or occupied with other tasks (Jones & Endsley, 1996; Orasanu & Fischer, 1992; Orasanu, Martin, & Davison, 2001). For instance, in their analysis of the American 1420 accident on June 1, 1999, Dismukes and colleagues (2007) suggest “that task saturation interacted with other cognitive vulnerabilities to prevent the crew from recognizing that continuing the approach was not a good idea. Weather information trickled in piecemeal, and high workload made it harder to integrate this information and recognize that conditions were deteriorating” (p. 269).

4.2.1.1 *Time pressure*

Time pressure may also lead to decrements in judgment and decision processes. Laboratory studies showed that subjects who worked under a deadline spent less time looking at information or relied on fewer cues to arrive at a diagnosis or prediction than subjects who worked without time pressure (Keinan, 1987; Khoo & Mosier, 2008; McKinney, 1993; Wickens, Stokes, Barnett, & Hyman, 1993; Wickens, 2002). In particular, they tended to show selective information processing, for instance, by focusing exclusively on spatially salient cues or on negative attributes (Wickens, et al., 1993), and were less likely to entertain multiple hypotheses or to integrate information from various sources, especially in dynamically changing conditions (Kerstholt, 1994). Stress was found to induce subjects to minimize cognitive effort, often at the cost of accuracy and decision quality (Barnett & Wickens, 1986; Bronner, 1982; Mackenzie et al., 1993; Payne, Bettman & Johnson, 1988; Zachay & Wooler, 1984). They were likely to jump to premature conclusions, shift their decision criteria, lock into one problem-solving strategy, and shed or simplify tasks (Dörner, 1992; Keinan, 1987; Kerstholt, Passenier, Houttin, & Schuffel, 1996; Maule & Hockey, 1993; Olshavsky, 1979; Payne, 1976; Payne, Bettman & Johnson, 1988; Serfaty, Entin, & Volpe, 1993). Similar effects have been observed in analyses of crew decision-making behavior during flight simulations of off-nominal events (Fischer, Orasanu & Montalvo, 1993; Orasanu, 1990; 1994). Poor overall performance was associated with both faulty situation assessment and response selection. Compared to more effective crews, less effective crews gathered less information and were less thorough in diagnosing a system malfunction. They considered fewer options, showed less planning, especially for contingencies, and settled on easy, less optimal courses of action. When several problems occurred concurrently, less effective crews traded one problem for the other.

4.2.1.2 Ambiguous or inadequate information.

Crews routinely have to make decisions with incomplete information, or in the presence of vague or contradictory cues. Ambiguity may exist due to an absence of good data or system information (Lipshitz & Strauss, 1997). Poor interface design that does not provide adequate diagnostic information or action feedback can lead a crew astray (Dekker & Woods, 1999; Dekker & Lützhöft, 2004; Dekker & Woods, et al., 2010). For example, in the following accident the crew shut down the wrong engine partly because information about which engine had the problem was poorly displayed (AAIB, 1990).

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 physical flight environment also is a source of ambiguity. Weather is inherently ambiguous, constantly changing and may support opposing interpretations. A think-aloud study by Fischer, Orasanu and Davison (2003) revealed that pilots created optimistic or pessimistic—but equally plausible—situation models from the same weather information, dependent on which aspect they stressed and how they integrated individual items. Different interpretations led pilots to favor a cautious or riskier course of action (i.e., delay departure vs. accept takeoff clearance). While this study was not designed to examine SA errors (as there was no correct solution), it does shed light on the dangers associated with ambiguous conditions. 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 (see the research on belief persistence; e.g., Davies, 1997; Jelalian & Miller, 1984). For decisions that have expensive consequences, such as rejecting a takeoff or diverting, pilots may need to feel very confident that the change is warranted.

4.2.1.3 Technological environment

Characteristics of the automated systems – such as opacity or ‘clumsiness,’ can also hinder effective and efficient decision processes. From the introduction of cockpit instruments, the trend has been to present data in pictorial, intuitive formats whenever possible. For example, the attitude indicator presents a picture of ‘wings’ rather than a number indicating degrees of roll. Collision alert and avoidance warnings involve shapes that change color, and control inputs that will take the aircraft from the red zone to the green zone on the altimeter. Proposed navigational displays show pilots a series of rectangles forming a ‘pathway in the sky,’ delineating their flight path (Berenger, 2000; Wickens, 2000). Within seemingly intuitive displays, however, reside data

that signify different commands, aircraft states, or values in different modes. These data must be interpreted - what does this piece of data mean when shown in this color, in this position on the screen, in this flight configuration, in this mode of flight? Once interpreted, data must be compared with expected data to detect discrepancies, and, if they exist, analysis is required to resolve them before they translate into unexpected or undesired aircraft behaviors.

Moreover, before system data can be analyzed, it must first be located. This is often not an easy process, because as the aircraft cockpit has evolved, much of the systems information has either been altered in format or buried below surface displays. Automated systems typically analyze information and present only what has been deemed 'necessary.' In their efforts to provide an 'easy-to-use' display format, designers have often buried the data needed to retrace or follow system actions. Resultant system opaqueness interferes with ability to track processes analytically, a phenomenon that has often been documented and discussed (e.g., Woods, 1996; Sarter, Woods, & Billings, 1997). The data that would allow for analytic assessment of a situation may not only be opaque, but may not be presented at all or may be hidden. What the pilot sees is an apparently simple display that masks a highly complex combination of features, options, functions, and system couplings that may produce unanticipated, quickly propagating effects if not analyzed and taken into account (Woods, 1996). Woods and Sarter (2000), for example, in describing a typical sequence leading to an 'automation surprise,' note that "it seems that the crew generally does not notice their misassessment from the displays of data about the state or activities of the automated systems. The misassessment is detected, and thus the point of surprise is reached, in most cases based on observation of unexpected and sometimes undesirable aircraft behavior" (p. 331). The inability of pilots to track the functioning of cockpit systems is evident in often-cited questions they express when describing incidents:

- What is it doing now?
- What will it do next?
- How did I get into this mode?
- Why did it do this?
- I know there is some way to get it to do what I want.
- How do I stop this machine from doing this?
- Unless you stare at it, changes can creep in. (Weiner, 1989; Woods & Sarter, 2000)

Highly-coupled autopilot modes increase the complexity in the cockpit. Sherry and his colleagues (Sherry, Feary, Polson, & Palmer, 2001; Sherry, Feary, Polson, Mumaw, & Palmer, 2001) decomposed the functions and displays of the vertical navigation system (VNAV) and of the flight mode annunciator (FMA). They found that the VNAV button is 'overloaded' in the descent and approach phases of flight, in that its selection results in the engagement of one of *six* possible trajectories - and that these trajectories will change autonomously as the situation evolves. Moreover, the same FMA display is used to represent several different trajectories commanded by the VNAV function. It is impossible to utilize this system intuitively; however, the interface does not provide the necessary information to establish or reinforce correct mental models of system functioning through analysis (Sherry et al., 2001b).

Complexity and opaqueness also may result in 'system-induced misinterpretations,' that is, cases in which crews, in the absence of analytical information or an accurate mental model, end

up making false inferences about the source or nature of a problem and how to resolve it. Plat and Amalberti (2000) observed glass-cockpit crews flying LOFT (Line-Oriented Flight Training) scenarios, and tracked their strategies for handling system faults and failures. Among the principal traits they documented in handling problems for which no procedure was recommended by their electronic assistance system was a "spontaneous tendency to improvise, reset circuit breakers or higher functions, and make (incorrect) inferences anytime the system becomes difficult to understand" (p. 305). Although crews were able to maintain control of the situation, their methods sometimes included 'tricks' found by chance, which allowed them to bypass a failure. Plat and Amalberti used the word 'magic' several times to describe the thinking and beliefs crews displayed concerning system functions and interactions.

The spontaneous generation of poor mental models of automated system functioning results in mistaken perceptions, and/or faulty attempts to manage systems coherently. The use of guesswork rather than informed situation assessment and decision making may continue in NextGen unless new automated systems are more transparent and easier to track.

4.2.2 Poor Team Communication and Coordination

Maintaining flight safety is a team effort and depends crucially on effective crew communication. Stress associated with off-nominal events may impair crew communication and coordination as team members narrow their perspective from the team to themselves (Driskell, Salas, & Johnson, 1999), thereby disrupting the benefits typically accruing from team collaboration. In full mission flight simulations poor task performance by crews was associated with specific communication defects that are consistent with a loss in team perspective. Members of high-error crews shared less information than more successful crews, in particular concerning their plans and task management (Orasanu & Fischer, 1992). Their communications tended to violate normative communication patterns – that is, they deviated from standard sequences such as question-answer pairs (Kanki, Lozito, & Foushee, 1989)—rendering their discourse disjointed and incoherent (Silberstein & Dietrich, 2003). Captains were also more likely to ignore or dismiss suggestions by first officers (Orasanu & Fischer, 1992). Analyses of aviation accidents isolated further problematic aspects of crew communication, especially indirect speech and ambiguous references (Cushing, 1997; Fischer & Orasanu, 2000; Linde, 1988). These communication failures may jeopardize crew decision making in significant ways. On the one hand, these failures likely add to crew members' workload and stress, as unclear utterances may require additional cognitive processing and repair sequences. Moreover, when critical information is not clearly communicated or shared at all, team members may not develop a common understanding of their situation and available options. And lastly, lack of communication and unresponsiveness by captains may discourage junior crew members from monitoring and if necessary challenging captains' decision making. This issue has been identified as the dominant contributing factor in aviation accidents in which tactical decision errors by captains were the primary cause (NTSB, 1994).

4.2.3 Individual Cognitive Factors

Pilots are responsible for four "meta tasks" in flight – they need to aviate, navigate, communicate, and manage systems (Wickens, 2003). Each of these requires attention to information and cues in the cockpit and/or external environment, such as warning lights, weather indications, position information, equipment status, or visual topography, in order to accurately assess the state of the world. For example, the recognition of an imminent stall is dependent on

the observation of cues such as the stall warning device and a reduction in control effectiveness. The failure to recognize such important stimuli can result in a dangerous situation being overlooked. Features of the cues can facilitate or hinder their detection.

4.2.3.1 Salience

Individuals are hardwired to deploy greater attention to sensory information that is salient. As a result, environmental cues that stand out relative to neighboring items due to their visual or acoustic properties (such as loud noises, bright lights, or those that appear in the fovea) are more readily attended to than less salient cues. At best, salience and importance are highly correlated; at worst, critical non-salient cues may be ignored. For example, the salience of auditory cues influences the extent to which they will be noticed and is integral to how the aircrew will respond to them. Arrabito (2009) found that acoustic properties such as the frequency, intensity, and repetition rate of non-verbal auditory warnings affected their perceived urgency inside a CH-146 Griffon helicopter. After assessing the pilots' rankings of the alarms in a post-experiment questionnaire, he found that the urgency of the triggering situation was influenced by the physical characteristics of the alarm: "siren-like" alarms were judged as the most urgent while continuous and stable alarms were judged as the least urgent. Arrabito (2009) also showed that the acoustic characteristics of verbal cockpit warnings influenced the performance of pilots. While performing a visual pursuit tracking task, participants were required to identify the verbal cockpit warning word that might be presented periodically over the headphones. In the absence of background speech, participants showed high accuracy in warning word identification, regardless of whether they were instructed to emphasize the listening task or the tracking task. However, the introduction of speech babble that simulated cockpit radio communication resulted in significantly lower accuracy in warning word identification, which was interpreted as due to the reduced salience of the warnings.

Visual detection of changes in aviation displays is also highly dependent on the salience of cues. In a series of experiments by Wickens, Muthard, Alexander, Van Olffen, and Podczerwinski (2003), student pilots were required to detect changes in the airspeed and heading or altitude of traffic aircraft and weather systems, using an integrated hazard display. When the traffic domain was highlighted, pilots showed superior detection of traffic changes and degraded detection of weather changes. Conversely, when the weather domain was highlighted, pilots showed superior detection of weather hazards and degraded changes of traffic changes. Because the highlighted domain was more salient, critical changes that took place in the non-highlighted parts of the display were less noticeable and more likely to be missed. As well, performance declined for the detection of changes located near the perimeter of the display, consistent with the notion that the saliency of the foveal activity can hinder detection of critical events near the periphery. The results of the study show the importance of salience for detection of visual cues; critical cues that are near the periphery of vision or within a low-lighted portion of a display may likely go undetected.

Even when display elements are designed to be salient, pilots may not see them. Nikolic, Orr, and Sarter (2004), for example, found that individuals missed abrupt-onset stimuli when they were embedded in a dynamic, complex, data-rich multicolored display. Similarly, pilots of automated aircraft often do not detect the green outline box that annunciates a flight mode change when it appears on the complex Primary Flight Display (e.g., Sarter, 2000). Nikolic et al. related their findings to the phenomenon of inattention blindness, the failure to notice signals in one location when one's attention is directed toward another location (Rensink, O'Regan, &

Clark, 1997). Another phenomenon called “change blindness” is also a factor in failures to notice changes that occur simultaneously with other disruptions of a scene or display (Nicolic et al., 2004; Simons, 2000). These phenomena help to explain why visual cues and information are not attended to in the cockpit display, and Nicolic et al. suggest as a remedy the use of multiple modalities to convey information (see also Sklar & Sarter, 1999). As the complexity of displays increases in NextGen cockpits, the ability to attend to changes in modes, system state, or navigational position - especially when they are unanticipated – will be further eroded.

Decision errors can also occur when pilots rely on highly salient cues that provide inaccurate diagnostic information about the situation. For example, sensory information is a powerful, salient cue that may be highly unreliable. Perceptual errors develop when sensory information does not accurately reflect the movement of the aircraft. When these visual or vestibular illusions occur, the aircrew is at risk of misjudging their own position in a three dimensional space, and therefore endangering flight safety. Spatial disorientation, for example, accounts for 6-23% of major accidents and 15-69% of fatal accidents in military aviation (Newman, 2007). To prevent these illusions from causing tragic accidents, pilots are taught not to navigate the aircraft by sensory input alone, but to check their primary instruments.

4.2.3.2 Information Integration and the Limitations of Expertise

The knowledge and cognitive abilities that define domain expertise vary according to whether coherence (consistency; rationality) or correspondence (accuracy) is the primary component of decision making. When correspondence is primary, expertise entails knowing which of the multiple fallible indicators to look for and rely on, and how to use and act upon these indicators. Expertise in a coherence-based task requires knowledge of how a system works, and the ability to describe the functional relations among the variables in a system (Hammond, 2000). Moreover, expertise within a domain does not ensure expertise in decision making within that domain. "Cognitive competence takes two forms; first and foremost is subject matter competence (often called domain competence); the second form is judgment and decision making competence....This is an important distinction to grasp, for it is often mistakenly assumed that domain competence assures process competence, or competence in judgment" (Hammond, 2000, p. 32).

Much of the applied work that has been done on expert judgment and decision processes in aviation has focused on correspondence. Klein's model of expert Recognition-Primed Decision Making (e.g., Klein, 1993; Klein, Calderwood, & Clinton-Cirocco, 1986), as discussed earlier, describes expertise as the ability to identify critical cues in the environment, to recognize patterns of cues, and to understand the structural relationships among cues. Expert pilots typically exhibit high correspondence ability. Their expectations of the environment have been shaped by a wide array of experiences, and they utilize these experiences to assess patterns of cues. For example, while executing a landing the pilot may check to see if the view out the window ‘looks right’ with respect to patterns of surrounding and runway lights, and whether the cues match what he or she has previously encountered at this location or point in the flight. Experts look for familiar patterns of relevant cues, signaling situations they have dealt with in the past, and base their responses on what they know ‘works’ (e.g., Klein, 1993; Klein, Calderwood, & Clinton-Cirocco, 1986). This expertise makes their correspondence judgments and subsequent decisions more likely to be accurate. Training for correspondence competence, in fact, often involves repeated exposure to specific types of situations, via paper-and-pencil exercises or computer simulations (e.g., Klein, 2000).

A large body of literature exists extolling the virtues of expertise and expert "intuition" (e.g., Dreyfus, 1997; Gigerenzer, 2007; Klein, 1993; 2003). The "intuition" discussed in this literature actually describes the situation-recognition-based decision processes typically utilized by experts. Expert pilots may use a combination of situation assessment (which is accomplished via pattern recognition), and knowledge gained through experience and past analyses to make judgments that appear to be 'intuitive' because they are relatively fast and do not involve computations. Their responses, however, are rooted in a breadth of knowledge garnered from years of analyzing situations and patterns in the environment. Experience, then, is a key factor in improving correspondence competence to the point of expertise.

In the hybrid ecology of the cockpit, however, correspondence may not be the primary responsibility of the human – the automated systems accomplish most of these judgments by transforming probabilistic cues into precise information. The pilot does not have to evaluate height and distance from the runway – the instruments display the aircraft position reliably and accurately. In the electronic environment, the primary task of the pilot is to supervise and monitor systems and information displays to ensure coherence – consistency of the picture presented with what is expected and required for current flight status. Managing the hybrid ecology is primarily a coherence-based, complex, cognitively demanding mental task, involving data, rationality, logic, and an analytical mode of judgment. Pilots must know about potential pitfalls that are the artifacts of technology such as mode errors (i.e., executing a function or command that is not appropriate for the current system mode; Sarter, Woods, & Billings, 1997), hidden data, or non-coupled systems and indicators.

4.2.4 Operator State

Empirical laboratory research has shown that a number of operator state factors may influence the quality of situation assessment, information processing, and decision processes (Peters, Västfjäll, Gärling, & Slovic, 2006). These findings have implications for crews' decision making and their handling of disagreements and conflicts with other players, especially air traffic controllers. The influence of operator state may manifest itself in different ways. First, it may limit –and thus bias—information search. Anger, for example, is consistently linked with heuristic processing (e.g., Lerner & Tiedens, 2006). This tendency may exacerbate operational phenomena such as automation bias (Mosier, Skitka, Heers, & Burdick, 1998) and automation-induced complacency (Parasuraman, Molloy, & Singh, 1993), which entail curtailed information search. In contrast, anxiety or worry have been associated with systematic information processing, but may also lead to over-vigilant attention to all available data, whether relevant or not, and delay of action (e.g., Loewenstein & Lerner, 2003). Second, operator state may guide the focus of cognition. Anger for example may encourage a 'blame' mode, in which operators focus on responsibility and retribution rather than problem solving. Fear or anxiety, in contrast, may elicit a concern for self-protection and safety. Operator state may also influence risk perception and risk-taking behavior. Anger was found to increase risk-seeking behaviors and was associated with the perception of personal control over a situation, whereas fear and anxiety led to risk-averse choices and the perception that a situation is not under one's control (Lerner & Keltner, 2001). Influential operator states may be induced by the conditions of operational situations themselves such as information overload, frustration, or fatigue. Conflict within a flight crew or between flight crew and air traffic control can both exacerbate these states and be affected by them.

Mosier et al., (2010) examined situational and individual variables in a set of ASRS reports to characterize the context in which incidents occurred. Patterns with respect to time of day, phase of flight, and airport were noted, as well as the types of conflicts that were prevalent. The focus of the work was to determine whether and what operator states would surface in accounts of conflict or communication breakdowns between pilots and ATC, as well as to evaluate the relationships among conflict, operator states, risk perceptions, and conflict resolution strategies. Although this study yielded only descriptive data, it can provide insights into potential problem areas and conflict triggers in NextGen operations. For example, the reports suggest that high workload associated with approach and landing phases is conducive to communication conflicts, particularly when changes to flight plans or runways are imposed or requested. NextGen operations will require these phases of flight to be precisely timed and flown at major airports, as traffic is predicted to almost double from current levels and spacing between aircraft will be reduced. This means that the potential impact of conflicts on traffic flow will be amplified.

The data hint that certain types of conflicts may be ameliorated or increased in NextGen operations. New integrated information sources may alleviate informational conflicts, as both ground and flight deck will have access to the same integrated information sources. However, cognitive conflicts associated with information interpretation, as well as with the differing perspectives and goals noted in current operations (Bearman, et al., 2010), may be exacerbated in NextGen operations. In particular, different interpretations of the same information (e.g., weather, traffic) in terms of its implications for safe and efficient operations may surface more frequently than in current operations. A collaborative and cooperative relationship between aircrews and ATC will be essential to avoid such conflicts.

The data also suggest that operator state may impact communication and collaboration between flight crews and ATC. Over half of the reporters described themselves or the other party with affective overtones and/or characterized actions with affect-laden terms. A specific problem was noted when reporters felt that the affective response of the other party did not match his or her own, or was not appropriate to the situation. The move to datalink communications may have a positive impact on this dynamic in that communications will be scripted and pilots and ATC will not have access to the tone of each other's voices. However, other sources of communication conflict such as delayed clearance delivery, repeated uploading of requests, or providing incomplete information may surface. Additionally, voice communications in NextGen are likely to be used primarily in off-nominal or emergency situations – precisely the situations that tend to evoke affective reactions – increasing the possibility that operator state will impact these critical communications.

4.2.4.1 Stress and fatigue

Irregular hours and long on-duty times as well as stress-inducing factors such as noise, vibration, time pressure, or threats or hazards are inescapable facets of commercial aviation operations. These operational variables may negatively impact attention and cognition, and in turn lead to faulty decision making (Orasanu, 1997).

One potential impact of stress on situation assessment is to produce attentional tunneling, and cause decision makers to focus on a limited set of cues and information. Time pressure, in particular, may induce less thorough and more heuristic use of cues and information. Stokes, Belger, and Zhang (1990) showed that in a dynamic, time-limited task, exposure to stress in the form of white noise exacerbated the tendency to attack only salient targets and to neglect less

salient ones. In other work involving regional airline pilots responding to web-based scenarios, Mosier, Sethi, McCauley, Khoo, and Orasanu (2007) found that time pressure had a strong negative effect on the coherence of front- and back-end processes, and that the presence of non-congruent information heightened these negative effects. Pilots were significantly less thorough in their information search when pressed to come to a diagnosis quickly than when under no time pressure. This meant that they tended to miss relevant information under time pressure, resulting in lower diagnosis accuracy - particularly when information conflicts or incongruencies were present.

Much has been written on fatigue, another stressor for flight crews, and recommendations abound for countermeasures or fatigue averting interventions such as caffeine, naps, or activity breaks (e.g., Bonnet et al., 2005; Mallis, Banks, & Dinges, 2010; Neri et al., 2002; Rosekind et al., 1994). Sustained attention and vigilance in monitoring and information search are some of the cognitive processes most susceptible to degradation under fatigued states (Mallis, Banks, & Dinges, 2010). This has critical implications for performance in highly automated cockpits, where little interaction with systems is required, while pilots must be constantly alert to changing status indicators or irregularities in the displays. Vigilance-related effects of fatigue are likely to be exacerbated in NextGen operations, when the use of 4D trajectories and increasing levels of automation for navigation and spacing make interaction with systems even less frequent than it is in current operations. Fatigue may also affect back-end decision processes, as it has been demonstrated to increase risk taking in decision making (Harrison & Horne, 2000).

Team members may experience difficulty communicating when stressed or sleep deprived. Both production and comprehension of language may be affected. While acoustical and phonetic changes such as pitch, amplitude, vibration, and voice onset time (Lieberman, Morey, Hochstadt, Larson, & Mather, 2005) may be good indicators of stress, they may not affect team communication as much as changes in lexical or content aspects. For example, when stressed, speakers often revert to clichés or other less explicit expressions (Cushing, 1994; Davison & Fischer, 2003). These include use of exophoric (e.g., ‘this,’ ‘that,’) or generic pronouns (‘it’) in place of specific nouns, thereby placing a greater burden on addressees (Harrison & Horne, 1997; Stokes, Pharmer, & Kite, 1997; Tilley & Warren, 1984). In simulated military operations following 36 hours of sleep deprivation, team members requested less information and engaged in less discussion of strategy regarding movement of assets or coordination of team actions than when rested (Harville, Barnes, & Elliott, 2004). The frequency of these critical communication behaviors declined with increasing hours of sleep deprivation. Language comprehension ability may also be impaired under stress, either due to distraction, i.e., difficulty focusing, or to more fundamental cognitive processes (Lieberman, Morey, Hochstadt, Larson, & Mather, 2005; Pilcher et al., 2007).

Moderate levels of either fatigue or stress may actually have a positive effect on pilot performance. Research on human motivation has long demonstrated that an inverted-U function best describes the relationship between stress/arousal and performance, such that moderate arousal produces better performance than either very low or very high arousal (e.g., Yerkes & Dodson, 1908). Moderate levels of fatigue, for instance, led participants managing a process control task at night to verify the functioning of an automated decision aid more often than those performing the task during the day – making them less susceptible to automation bias and commission errors (Manzey, Reichenbach, & Onnasch, 2009).

4.2.4.2 **Expertise and operator state**

Does operator state play a role in expert decision making? It is desirable to posit that experts are able to ignore affective states such as fatigue or stress during decision processes. Excluding state variables from the discussion of expert decision making, however, may be short-sighted. States and emotions are not necessarily irrelevant distractions but rather may provide valid information about the task at hand. Evidence in support of this assumption comes from the relatively new field of cognitive neuroscience. Research has identified neural circuits that process the emotional significance of stimuli and interact with cognitive systems (Cacioppo, Gardner, & Berntson, 1999; Ochsner, et al., 2009). The emotional significance of stimuli enhances their salience, directs attention, and supports memory consolidation (see review by Phelps, 2006). Cosmides and Tooby (2000) view emotions as superordinate programs that activate and coordinate cognitive and physiological processes as well as behavioral responses. Consistent with this view, Damasio (1994) reports that patients who lost their ability to process emotional stimuli normally also showed marked defects in their decision making ability.

It seems therefore important to distinguish between task-relevant affect and emotions that are extraneous to the problem individuals try to solve. This distinction is critical to the discussion of affect in expert decision making because experts have been shown to be selectively sensitive to task critical information (c.f., Chi, Glaser, & Farr, 1988). Accordingly, experts unlike laypersons may differentially respond to task-related and unrelated affect. This assumption has two implications: 1) Experts may be able to identify emotional responses that are not relevant to the task at hand and thus prevent them from impacting their decision making. That is, experts may be good at identifying potentially intrusive states and at emotion control. For example, in the ASRS study above, pilots noted that they were cognizant of states that might negatively influence their decision making, such as aggravation or agitation (e.g., Mosier et al., 2009). 2) Experts may be well attuned to affect that is in response to critical elements of the task context and that may have significance for their decisions. Emotional cues may have signal character that triggers appropriate responses without much deliberation. In that sense emotional cues may be part of recognition-primed decision making.

For experts, then, affective reactions to situations (i.e., task-relevant affective responses) may represent a knowledge-based informational cue, and may be a salient component of their decision making. Moreover, they may look for evidence of similar responses in other team members. As mentioned in the previous section, pilots in the ASRS study sometimes expressed concern or discomfort about clearances they were given - and expected ATC to respond with similar affective tone. In fact, one pilot reporter wrote that “We are very concerned about his [the controller’s] apparent lack of concern” (ASRS #486349; Mosier et al., 2009).

Experts’ emotional reaction to cues may also provide a frame for their sense-making and, as predicted by the Appraisal Tendency Framework (e.g., Ellsworth & Scherer, 2003), may guide their information search and integration. As an illustration, consider the following quotes from a study by Fischer, Orasanu, and Davison (2003) in which commercial pilots verbalized their thoughts during hypothetical aviation decision scenarios. The first two quotes are by pilots in response to a potential windshear situation at takeoff. The last quote occurred in response to an approach scenario. (Italics added for illustration purposes.)

Subject 24 (First Officer): “See whether ATIS has anything, or Tower reports...“moderate rain” now start seeing some effect of that, the runway is grooved as

you showed me earlier...starting to get close, *starting to get into my comfort zone*. But I still would continue to go ahead...may look at my take-off data one more time ...”

Subject 8 (Captain): “Well, I tell the passengers that that I made a decision not to take off because of the weather and that ... other pilots may choose to go but my level of...*my level of comfort... was exceeded* by the way the thunderstorm is coming to the airport”

Subject 33 (Captain): “... at this point I think I’d be *getting pretty concerned about my fuel situation, real concerned*, and I’d be talking to dispatcher and asking for...feedback from them and see where they want us to go ‘cause now I am thinking I don’t even want to fool with this airport anymore...because if they got thunderstorms in the area we’ve got traffic problems...*I’m not comfortable with 11 thousand pounds of fuel on my airplane*,,, I’m totally in a divert mode. I wanna go somewhere else already. *I don’t like this*...even though the weather is going to clear up that there’s still a bunch of airplanes out here to get on the ground...

As flight conditions changed over time, pilots apparently used their affective reactions to decision-relevant information to frame their decision making. Logistic regression analyses using pilots’ positive and negative evaluations of features in the flight context as well as statements reflecting non-evaluative cognitive processes (e.g., planning) as predictors indicated that pilots’ level of comfort in response to a flight situation apparently shaped their interpretation of information and ultimately their decision (Fischer, Orasanu, & Davison, 2006). In the Approach Scenario pilots who expressed optimism about the conditions, the likelihood of landing at their original destination, and making the curfew were likely to continue with the approach; pilots who viewed conditions more negatively tended to divert. Similarly, pilots who decided to depart in the Takeoff Scenario evaluated the weather and airspeed loss more positively than did those who delayed the departure. They tended to emphasize the fact that the weather was behind them, still 8 miles away, and that the departure path was clear. In addition, they focused on the quantity of airspeed loss, which they considered to be within limits, and interpreted the reported decrease in airspeed loss as an indication that weather conditions were improving. In contrast, pilots who delayed the takeoff were primarily concerned about the airspeed loss per se and took the variability in reported airspeed loss to indicate unstable winds. In line with this interpretation, they stressed the fact that the weather was getting closer. Because they assumed that they could not outrun the storm and that the winds were becoming unpredictable, they decided not to risk a takeoff but instead to wait for the weather to pass.

4.3 Human Tendency toward Heuristics and Biases (H&B)

Humans have a tendency to take the path of least cognitive effort (e.g., Fiske & Taylor, 1991). When time or mental resources are limited, they will often use cognitive shortcuts to reduce the work needed to make probabilistic judgments. This type of non-coherent (i.e., not rational) decision making involves the use of cognitive heuristics, or rules of thumb. Although these heuristics enable humans to make decisions that are fast and accurate most of the time (e.g., Gigerenzer, 2007, 2008), they may lead to cognitive biases that form the basis of irrational judgments because they do not take into account all of the information required for the complete assessment of the situation (Tversky & Kahneman, 1974). Indeed, dozens of cognitive biases have been studied extensively and experimentally verified, and researchers have developed

taxonomies in order to provide people, such as decision support systems analysts, with a clearer perspective of the impact decision biases have on decision making.

Most of the research on H&B has involved naïve participants responding to word problems; research addressing H&B in aviation has focused on general aviation pilots. Very little research has been accomplished with professional pilots or other experts as participants. This shortcoming severely limits the generalizability of most H&B results to decision making in the commercial flight deck. The heuristics of experienced pilots making judgments within their domain may be different from those of less experienced pilots or naïve participants, and they likely know when a situation affords the use of heuristics and when it does not. Expert pilots' heuristic principles are grounded in rich knowledge structures, and their heuristic-driven processing may be the rule rather than the exception; as Orasanu (1993) notes "cockpit decisions are heuristics" (p. 139). What must be kept in mind is the store of knowledge that guides expert pilots' shortcuts and makes them less susceptible to bias. Because experienced flight crews have a broad, representative knowledge base at their disposal, the heuristic principles they use are likely to be more sophisticated and context-sensitive than those of novices, and as a result less prone to errors and biases. (One notable exception is automation bias – errors resulting from the heuristic use of automation as a replacement for vigilant information search. This bias has been found in expert pilots, and is discussed later in this section.)

Wickens and Flach (1988) proposed an often cited model of aeronautical decision making that incorporates references to H&B. The model, developed around general aviation pilots rather than experienced flight crews, suggests a sequence of information processing components relevant to pilot decision making (cue seeking, situation assessment, option generation, option selection, and action), along with cognitive biases that arise from the inappropriate use of heuristics and that may influence specific stages of the process. Many of these shortcuts are not errors per se; rather, their effectiveness depends on the pilot's knowledge store.

4.3.1 Representativeness

When choosing a hypothesis, individuals frequently use the cognitive shortcut known as the representativeness heuristic. It refers to people's tendency to judge the probability of an event based on the degree to which it has similar characteristics to a past event. Thus, when pilots need to quickly diagnose a potentially dangerous situation, they may recognize familiar cues seen in the environment and 'pattern match' those cues with situational schemata as recalled from long-term memory.

O'Hare and Wiggins (2004) investigated the usefulness of the representativeness heuristic among a large sample of survey respondents, most of whom were recreational pilots. More than half of 1081 respondents reported an instance in which their response to a critical flight event had been influenced by the recollection and utilization of a previous case. As expected, respondents noted that the cases were more likely to be recalled during the early stages of the critical flight event, consistent with the notion that individuals use the representativeness heuristic during problem diagnosis. Importantly, the vast majority of pilots (89.3%) found the previous case to have been moderately or very useful, and 84% of the pilots believed the previous case to have played an integral role in their response to the event.

While O'Hare and Wiggins (2004) suggest that the representativeness heuristic is more frequently helpful than not, it may also lead pilots astray. For instance, pilots may come to an incorrect diagnoses if they believe that the current situation is similar to an event they have experienced in the past, but it is not. While novice pilots may be more prone to this error than

expert pilots, over-reliance on representativeness may have played a role in commercial aviation accidents. For example, Nagel (1989) suggests that the representativeness heuristic may have mis-guided the decision making of the Air Florida crew that crash-landed in the Potomac River on January 13, 1982. The crew, inexperienced in flying in cold weather, did not activate the anti-ice system for takeoff despite the fact that it was snowing. Nagel hypothesizes that the crew's ability to imagine that their engine power readings were improper because of accumulations of ice or snow may have been impaired by the *overwhelming representativeness* of their current takeoff conditions to successful takeoffs in the past: engines spooling up, power indications appearing to correspond appropriately, no exceptional warning signals, and so forth. Their cockpit voice recording suggests that the crew did notice that the engine power instrument readings were well in excess of normal takeoff thrust, even though the throttle settings corresponded to normal takeoff power. Rather than imagining the readings to be faulty, the pilot's comments indicate clearly his judgment that the apparent increase in power must be due to what were for him unusually cold conditions. In other words, he apparently thought that the engines were more efficient in the cold! (paraphrased from Nagel, 1988, pp. 289-290).

4.3.2 Availability

When judging the plausibility or probability of hypotheses or diagnoses, individuals may think of instances they know and take the ease with which they can retrieve these from memory as the basis for their judgment. Underlying this heuristic is the assumption that ease of recall correlates with frequency of encounter. Biased judgments result when the availability of an instance reflects its vividness or recency, rather than its likelihood or frequency. Individuals' perceptions of the likelihood of events are often influenced by high-profile, vivid events, leading them to overestimate the chance that such events will occur. For example, after a midair collision or a bird strike, the media's vivid coverage heightens the event's availability in memory, and consequently some, especially inexperienced, pilots may over-estimate the probability of like events.

Use of the availability heuristic among expert pilots, however, is likely to result in correct diagnoses and situation assessments. Domain experts have learned to extract and attend to critical, relevant cues, to assess cues more accurately, and to discern complex interactions among cues (Einhorn, 1974). For expert pilots, retrieval of the most available experience in memory will be based on this knowledge, and they will be more likely than novices to retrieve an appropriate event. Recognizing a situation as typical and familiar sensitizes the expert pilot to important elements of the situation, and sets up expectancies about what is likely to happen and when. Importantly, experts use these expectancies to test situation assessment; failure of expected events to materialize or the occurrence of unexpected events will trigger reassessment of the situation (Klein, 1993a, b).

Interestingly, Schuch (1991) discussed an instance in which the lack of available experiences may make experienced pilots more prone to complacency than novices. He noted that midair collision accidents typically involve experienced pilots. This is surprising, considering the fact that visual scanning ability is expected to improve with experience. Schuch hypothesized that experienced pilots' behavior may reflect desensitization to traffic dangers after numerous repeated flights without incident. This hypothesis was based on his finding that inexperienced pilots had an unrealistically high perception of midair collision risk, and scanning for traffic was thus a top priority for them. Experienced pilots, in contrast, had developed a more

realistic perception of the actual risk of midair collisions due to a history of incident-free flight; as a result, they lowered the priority of visual traffic scan.

4.3.3 Confirmation bias

During situation assessment, pilots continuously search the environment for critical cues in order to update and improve their comprehension of the situation. However, their search behavior may favor evidence that confirms rather than disconfirms what they already believe to be true (Wickens & Flach, 1988; Hooey & Foyle, 2001). This behavior, known as confirmation bias, may cause pilots to focus attention on sources of information that are consistent with their initial assessment or expectations, while ignoring or minimizing sources that refute it, as in this example:

On descent [into Lexington, Kentucky, a crew] broke out of the clouds about 6000 feet above the ground and were asked by ATC if they had the LEX airport. The Captain looked [across the] cockpit at the LEX DME, located on the first Officer's side, and, due to parallax, saw "9" – it was reading "29" ... The external picture looked good, city lights past the airport on the left, similar runways, and when they keyed their radio mikes to illuminate the runway lighting, the lights came right on...in Frankfurt, Kentucky and that is where they landed. (Maher, 1989)

Muthard and Wickens (2002) tested the hypothesis that confirmation bias contributes to plan continuation errors (Orasanu, Martin & Davison, 2001); that is, they hypothesized that pilots continue with their original flight plan in the face of changing conditions because they focus on evidence in support of that flight plan, while ignoring cues suggesting it might no longer be viable. Using a low fidelity simulation, they presented general aviation pilots with a graphic display of two flight paths and potential hazards (terrain, weather, other traffic). Pilots were asked to select a flight path that cleared the hazard, and subsequently were required to monitor the safety of the route by detecting safety-critical changes in traffic and weather systems. During the experiment the risk level of their initial choice of flight path was increased surpassing the level of the alternative, such that optimally the pilot should revise his or her original selection. Muthard and Wickens predicted that if confirmation bias were present, pilots would more easily detect cues in support of their initial path choice than detect cues that refuted it. However, the opposite behavior was observed; pilots were faster and more accurate in detecting changes that refuted their hypothesis compared to confirming and neutral changes. The authors concluded that only a minority of pilots fall prey to confirmation bias; however, overall accuracy in detecting change was relatively low.

Research with experts has shown mixed results with respect to confirmation bias. Contrary to Klein's (1989) finding that expertise ameliorated confirmation bias, Cook and Smallman (2008) observed that experienced naval trainee analysts and reservists did exhibit confirmation bias in their selection of evidence in a realistic intelligence analysis task; however, this bias was mitigated by a graphical evidence layout (rather than text). Similarly, Hooey and Foyle (2001) report findings that point to the presence of confirmation bias in professional pilots' decision making. A post-hoc analysis of data from two full-mission simulation studies showed that three of six pilots who were given a clearance requiring a turn away from the concourse deviated from the cleared route by ignoring a taxiway. The researchers speculate that these pilots expected a particular clearance because of their knowledge of the airport layout. When the actual clearance conflicted with their expectations, they believed that they had misheard the clearance and

ignored the extra taxiway element. The authors concluded that confirmation bias may be one of the main contributing factors to planning errors - errors in which the pilot formulates an erroneous plan or intention, and then makes navigation decisions based on the incorrect plan.

4.3.4 Framing

After assessing a problem situation, the pilot must choose what action to take. Analytically, this process would require the pilot to evaluate each possible action by employing risk assessment and criterion setting to ensure that the most appropriate response is chosen. Each option (e.g., continue on, land immediately) can be described in terms of probable outcomes (e.g., reach airport, disastrous landing) and associated probabilities (e.g., likelihood of having enough fuel). The pilot should optimally choose the course of action with the lowest expected risk. Biases that have been hypothesized to influence this process are the framing effect and overconfidence.

The framing effect refers to the finding that manipulating the description of statistically identical options in terms of either gains or losses can alter an individual's decision preference. Tversky and Kahneman (1981) observed that people were risk averse when decision options were phrased positively in terms of gains, and more risk seeking when the options were phrased negatively in terms of losses.

Alternatives are seldom presented to the pilot in terms of choices with probabilities, as in the Tversky and Kahneman lab studies. Rather, it has been suggested that pilots create either a positive or negative frame of a situation by the factors they consider and emphasize in their situation assessment (e.g., gains such as safety vs. losses such as missed passenger connections), and that their choice of a risky or safer option will be impacted by that frame. Although anecdotal evidence suggests that this may be the case, empirical research evidence that documents the existence of framing effects on risky decisions among professional aircrews is scant.

One of the few studies that purports to measure the impact of framing in aviation was conducted by O'Hare and Smitheram (1995). Using general aviation pilots, they examined the framing effect on pilots' choices during a part-task simulation of a cross-country flight with weather conditions changing from VFR to IFR. Prior to the simulation, participants were presented with opposing decision frames highlighting gains or losses and asked to indicate the frame that best reflects their thinking during in-flight decisions. Results indicated that pilots preferred to frame decision options in terms of gains; however, their chosen frame did not influence their subsequent decision. In a second flight scenario pilots were presented with either a positive or a negative assessment of the current situation. This type of framing showed the predicted effect: pilots for whom their current situation was characterized in terms of cumulative losses (e.g., time, money, or effort invested so far) were more inclined to continue into severe weather than those for whom money and time investments were described in terms of gains; However, the faithfulness of their framing manipulation to the Kahneman and Tversky model is questionable, as is the generalizability of their results to experienced flight crews.

Anecdotal evidence of risk-seeking behavior of pilots induced, for example, by organizational frames created by policies that emphasize loss outcomes does exist. Mosier-O'Neill (1989) noted that Braniff International's 1968 policy to curtail late arrivals created a powerful loss frame – although it is not clear whether the company's measure influenced pilots' evaluation of decision alternatives—as predicted by traditional framing research—or their risk assessment—as suggested by NDM research:

The “fast buck” program initiated by Braniff International in 1968 required the airline to pay each passenger a dollar if a flight did not arrive at its destination within 15 minutes of schedule. This program may have contributed to the crash of a Braniff Electra Turboprop in May of that year. The flight had been delayed on departure and was pushing the 15-minute limit as it neared the destination airport. The crew attempted to penetrate a line of thunderstorms rather than navigate around them, and lost control of the aircraft in turbulence. (Nance, 1984, Chapter 6).

4.3.5 Overconfidence

People tend to overestimate the accuracy of their judgments, level of knowledge, and degree of control. For example, in a series of experiments, Lichtenstein and Fischhoff (1977) found that people overestimated the probability of being correct, especially for difficult problems. Several studies with private pilots have shown that they are unrealistically optimistic about their flight skills and their ability to assess flight situations correctly. As a result, they may underestimate their chances of being involved in an accident, and may therefore be more willing to take risks. For instance, Goh and Wiegmann’s (2001) study of general aviation pilots indicated that pilots who press on into deteriorating weather generally underestimated the risks involved in flying through adverse weather, and typically were more confident in their skill and judgment than those who chose to divert. Interestingly, Goh and Wiegmann did not find a framing effect in their data – pilots who chose to continue did not respond differently on the framing questions from those who chose to divert.

Experienced pilots also may fall prey to overconfidence in their skill level and their chances of avoiding harm through personal control, influencing their decisions in risky situations. Professional pilots have been shown to be particularly vulnerable to overconfidence when they use curtailed decision processes. In a study of information use in diagnosis and decision making, Mosier et al. (2007) found that confidence in diagnosis did not differ significantly as a function of time pressure (which constrained information search), or whether all the available information was consistent with a particular diagnosis. In fact, pilots’ confidence in their diagnoses was unrelated to their accuracy, and was negatively related to the amount of information they checked – the fewer items pilots checked, the more confident they were of their diagnosis.

4.3.6 Automation Bias

One bias that has been demonstrated across novice and professional pilot samples is automation bias. Mosier and Skitka (1996) noted pilots’ tendency to use automation as a heuristic in both front- and back-end processes. Because automated systems provide highly salient cues that are believed to be accurate and reliable, pilots tended to use them as a replacement for vigilant information seeking and processing, resulting in reduced situational assessment. Mosier and Skitka coined the term *automation bias* to describe this process and resultant errors. Mosier, Skitka, Heers, and Burdick (1998) provided empirical evidence for this phenomenon in a study of 25 commercial airline pilots flying a part-task simulator. Participants were presented with three flight related automation failures (e.g., an altitude clearance was misloaded into the flight control system), providing the opportunity for omission errors, and one false automated engine fire message, providing the opportunity for a commission error. Results showed that the automation failures were missed approximately 55% of time by pilots, and that *all* of the pilots who experienced the false engine fire message committed the error of shutting down a working engine.

The use of automation as a heuristic, particularly with respect to omission errors, has been related to inattention and complacency (Parasuraman & Manzey, 2010), but can also occur in the face of contradictory cues from other sources (e.g., Mosier et al., 1998; Reichenbach, Onnasch, & Manzey, 2010). Two key findings should be noted from the automation bias research: (1) experience and expertise were positively correlated with the error rates in the Mosier et al. (1998) study, suggesting that experience does not insulate pilots from this bias – and in fact that experience with highly reliable automated systems may exacerbate automation bias; (2) Pilots and lay participants made commission errors even when they claimed to look at other verifying cues. Mosier et al. (1998) attributed this to a ‘phantom memory’ effect – pilots erroneously remembered cues that would have corroborated the engine fire message (e.g., aural warning, master warning light), even though those cues were not present. Reichenbach et al (2010) observed a similar effect in that most of the participants that followed faulty automated advice despite verifying other system parameters could not correctly recall the status of those systems. They referred to this as a ‘looking-but-not-seeing effect.’

Certain types of aids may be more conducive to the use of automation as a heuristic than others. Unreliable back-end computer recommendations, for example, may lead to commission errors (as above in the false engine fire message) and worse performance than no computer recommendations. Layton, Smith, and McCoy (1994), for example, suggested that automated recommendations early in the course of problem evaluation may curtail situation assessment and exacerbate the tendency to use automation as a short-cut. Additionally, in the Sarter and Schroeder (2001) study discussed earlier, pilots were provided with either a status display that indicated the location of ice accretions on the aircraft’s surface, or command displays that also recommended to the pilot the appropriate power setting, flap setting, and pitch attitude. Pilots with the command displays performed better than pilots with the status display when accurate information was presented. However, when inaccurate information was displayed, the pilots with the status display showed superior handling of the icing encounter than those with the command displays. The authors suggested that, unless decision aids are perfectly reliable, status displays are preferred over command displays because the former are less vulnerable to the heuristic use of automation and resultant errors.

Because of increased demands for preciseness and efficiency, pilots in NextGen will be even more dependent on automation than they are in current operations, potentially increasing the tendency to use automation as a heuristic short cut. Although this will not be a problem in most instances, as the automated systems will be extremely reliable, flight crews will be highly vulnerable to automation bias and automation-related errors when systems do not function correctly, or when contextual factors or flaws in data make their information or recommendations incorrect. Training or other *debiasing* methods will be needed to guard against these errors.

4.4 When Do Heuristics Work?

Not all researchers and designers see heuristics as irrational. In fact, heuristics that are calibrated and adapted to features of the ecology have been viewed as adaptive tools. Some researchers posit that the key to using heuristics successfully is to match heuristics with environmental structures in which they work (ecological rationality). Gigerenzer, for example, has demonstrated that *fast and frugal* heuristics, such as *take the best* cue with the highest validity, result in judgments that are just as accurate as a more coherent multiple-regression model (Gigerenzer, 2008; Gigerenzer and Selten, 2001). The position he and his colleagues take

is that when heuristics are applied in situations “...to which they have been adapted...” they can be useful to professionals such as doctors (Wegwarth, Gaissmaier, & Gigerenzer, 2009, p. 1). Others have argued that in complex choice situations with much information, less deliberative thinking may result in more accurate decision making than conscious and rational deliberation (Dijksterhuis, Bos, Nordgren, & van Baaran, 2006; Maule, 2009). In fact, one approach to the design of decision support systems suggests to align them with the heuristic-based information acquisition strategies and preferences of users (Wiggins & Bollwerk, 2006).

The effectiveness of heuristics may depend also on their grounding in experience and knowledge. Experienced decision makers may rely on heuristic principles such as pattern recognition because they already have structured mental representations of their domain and have a breadth of knowledge behind the utilization of these shortcuts. Because proficient decision makers have a much broader, more representative database at their disposal, the heuristics they utilize are likely to be less prone to some errors and biases. Klein (1989), for example, found that more proficient decision makers were less susceptible than novices to confirmation bias, the tendency to seek out evidence that confirms one’s initial assessment; rather, they monitored the situation constantly for disconfirming cues. In other work, active U.S. Navy officers handling simulated state-of-the-art ship defensive systems were not influenced by outcome framing (Perrin, Barnett, Walrath, & Grossman, 2001).

4.5 Organizational Pressures: Safety Climate and Culture

This is at the heart of the professional pilot’s eternal conflict. Into one ear the airlines lecture, ‘Never break regulations. Never take a chance. Never ignore written procedures. Never compromise safety.’ Yet in the other they whisper, ‘Don’t cost us time. Don’t waste our money. Get your passengers to their destination – don’t find reasons why you can’t. (Wilkinson, 1994, in Dekker, 2006, p. 197)

The organization within which the flight crew resides exerts a degree of influence varying from subtle to explicit. Broadly, the organization sets the cultural norms in terms of decision priorities—safety, profit, quality, excellence, expedience, etc. These supposedly set the frame for decision making. An organization that has a *safety culture*, for instance, should promote judgments and assessments that weight safety aspects heavily and decisions that are conservative and entail low risk. The organizational *climate* prevalent in an organization, however, may or may not be consistent with stated norms and values. The climate motivates decision makers’ attitudes and behaviors, and is a product of their perceptions and beliefs about and emotional reactions to cultural elements as well as what is overlooked and what is rewarded (Helmreich & Merritt, 1998; Mearns & Flin, 2001).

...an airline’s commitment to safety can be easily determined by answering this simple question. Is there a gap between its policies and its practices? Colgan repeatedly states that safety is a top concern and yet, here’s the gap. Colgan claimed to have a policy prohibiting pilots from overnighing in crew lounges, yet it was a well known fact that commuting pilots did just that. Colgan claimed use of personal electronic devices was prohibited, and yet, the 24-year-old first officer on the flight not only felt free to send text messages, but when she did so, the captain failed to say anything to her about it (Huffington Post, Feb. 1, 2010, p. 1).

Pilots' perceptions of consistency between espoused culture and actual climate depend on whether the cultural norms are supported by aspects such as organizational processes (operations, procedures, oversight), resource management (allocation of human, monetary, and equipment resources), supervision, training, assignment of work, attention to existing rules, regulations, and standard operating procedures (see Shappell et al., 2007, for descriptions of organizational and supervision influences on behavior). Through its practices and priorities, the organization contributes latent circumstances that will influence the way individuals at all levels form judgments and make choices. For example, if the organizational culture espouses safety, but operators perceive that management is likely to compromise safety for profit, to reward expediency over safety, or even to punish safer but more costly decisions, operators are likely to assess situations in terms of their expense to the company and to select risky options (Bearman, Paletz, Orasanu & Brooks, 2009; Holbrook, Orasanu, & McCoy, 2003; Mearns & Flin, 2001; Mearns, Flin, Gordon, & Fleming, 2001). An organization's advertising campaign, slogan, or promotional programs can also have a direct impact on decision makers, as illustrated by the Braniff vignette earlier.

Pilots often deal with conflicting goals dictated by the organization, the situation, and their own judgment. In a society that has become increasingly litigious, some organizations prefer to 'cut loose' any decision makers whose choices turn out badly rather than dealing with any latent organizational conditions that may have fostered the choices. Failure on the part of the organization to support and back up operator decisions can have a chillingly negative impact on judgment and decision processes as well as the decision makers themselves.

Potential revelations about systemic vulnerabilities were deflected by pinning failure on one individual in the case of November Oscar 1. November Oscar was an older Boeing 747 "Jumbojet." It had suffered earlier trouble with its autopilot, but on this morning everything else conspired against the pilots too. There had been more headwind than forecast, the weather at the destination was very bad, demanding an approach for which the co-pilot was not qualified but granted a waiver, while he and the flight engineer were actually afflicted by gastrointestinal infection. Air traffic control turned the big aircraft onto a tight final approach, which never gave the old autopilot enough time to settle down on the right path. The aircraft narrowly missed a building near the airport, which was shrouded in thick fog. On the next approach it landed without incident.

November Oscar's captain was taken to court to stand trial on criminal charges [for] "endangering his passengers" (something pilots do every time they fly, one fellow pilot quipped). The case centered around the crew's "bad" decisions. Why hadn't they diverted to pick up more fuel? Why hadn't they thrown away that approach earlier? Why hadn't they gone to another arrival airport? These questions trivialized or hid the organizational and operational dilemmas that confront crews all the time. The focus on customer service and image; the waiving of qualifications for approaches, putting more work on qualified crewmembers; heavy traffic around the arrival airport and subsequent tight turns; trade-offs between diversions in other countries or continuing with enough but just enough fuel. And so forth. The vilified captain was demoted to co-pilot status and ordered to pay a fine. He later committed suicide. The airline, however, had saved its public image by focusing on a single individual who, the court showed, had behaved erratically and unreliably (Wilkinson, 1994, in Dekker, 2006, p. 62).

One important goal in NextGen will be to clarify the role of the organization and its influence on decision making behavior. Even decisions to adopt a cheaper but less transparent system display, for example, will likely have ramifications in terms of operator errors in decision making (e.g., Reason, 1997; Dekker, 2006; O’Hare, 2003). Many accident investigators now embrace a systemic approach when determining causes of accidents involving decision errors, and include latent organizational influences such as unsafe or poor supervision, inadequate training or resources, and disregard of rules or regulations (Dekker, 2006; Reason, 1990, 1997; Shappell et al., 2007).

5 Crew Decision Making in NextGen: Changes and Challenges

5.1 Critical Changes to Current Operations

Comments on NextGen impacts and changes appear throughout this document. In this section, we summarize some of the key changes and technologies that will affect how flight crews make decisions. Three aspects of Midterm NextGen operations will have probably the most significant impact on flight crew decision making: (1) changes in roles and responsibilities; (2) the proliferation of automation, particularly information automation; and (3) conversion to datalink as the primary communication mode.

5.1.1 Changes in roles and responsibilities

Decision making in NextGen will be a much more collaborative process than in current operations. It will be distributed among ANSP, flight crews, and flight planners, with the flight crew taking on a greater role in many tactical management tasks, as well as in strategic flight management (JPDO, 2007). The flight crew will become an equal partner with ANSP and airline operations centers in making air traffic management decisions. Flight crews will have more autonomy, accompanied by commensurate responsibility and the requirement for more of a systems perspective than is the case in current operations. This will entail increased communication and information exchange across the system to ensure that all participants have accurate shared mental models. Mixed equipage and different airline policies (e.g., with respect to whether flight crews or airline operations centers have authority and responsibility for specific decisions) will complicate this issue.

Using new automation, pilots will be able to assume separation and spacing responsibility, particularly in terminal operations and approach procedures such as merging and spacing around high-traffic airports and to closely spaced parallel runways (CSPR). It will be important to ensure a smooth transition of responsibility in these operations, so that it is always clear who is accountable for aircraft-to-aircraft separation. This will be especially critical when decisions must be made quickly, as, for example, when automation enables less space between aircraft and faster landing speeds.

5.1.2 Proliferation of automation

A primary enabler of collaborative decision-making is information, and much of the new NextGen systems will involve information automation. Flight crews will have access to weather and traffic information via technologies such as the 4-D Weather Data Cube and CDTI. Design decisions concerning the placement of information (e.g., electronic flight bags vs. primary displays), characteristics of its display (e.g., graphical vs. text), and accessibility (e.g., surface vs. layered or hidden) will impact how and how well flight crews can use this information. Formats that elicit intuitive and holistic processing should not require analysis for interpretation. Timeliness, accessibility, and comprehensiveness of information will be critical – a challenge to designers will be to ensure that the right information is available at the right time, especially when decisions need to be made under time pressure.

Management and control automation will enable trajectory based operations, very precise 4-D flight paths, and will decrease the need for active engagement in the flying task. This change facilitates efficiency in the airspace system, but presents challenges for the flight crew in terms of maintaining situation awareness and flight skills – particularly around off-nominal events. Because the automation will provide reliable and accurate data about the outside-the-cockpit environment, flying will be primarily a coherence-based task, requiring integration of information about navigational and system status.

The proliferation of automated systems also will have an impact on crew communication. While information in shared displays may support mutual understanding as it is accessible to both crew members and thus may not require explicit discussion. However, the fact that data are visually shared data does not guarantee that crew members develop a common situation understanding. Research by Fischer and colleagues (Fischer & Orasanu, 2000; Fischer, Orasanu & Davison, 2003; Fischer, Orasanu & Wich, 1995) showed that pilots interpreted identical information differently and integrated the same data into incompatible situation models. Automated systems that emphasize the interpretation and integration of information will challenge crew members to adjust their communication to this requirement.

5.1.3 Datalink communication

Although datalink has been used in the oceanic environment for some time, its elevation to the primary communication mode in NextGen operations will be a significant change and has implications for decision making, especially as increased communication among dispersed team members will be essential. For example, visual displays of traffic on the CDTI will replace party line access. This increases visual load, and may reduce information on other aircraft intent. Other aural cues, such as affective tone (e.g., urgency) will be unavailable on datalink. Error checking inherent in current pilot read-backs of clearances will be lost. Some information, such as ATC clearances, will be uploaded directly into the FMS. While this move may pre-empt current-day read-back and input errors by pilots, it also may impair flight crews' situation awareness as they are pushed into the role of a passive receiver of an information exchange rather than being an active participant in this communication.

A similar problem was observed when procedures involving the new National Route Plan (NRP) was implemented (Smith, McCoy, Orasanu, Billings, Denning, et al., 1997). Formerly, ATC coordinators in the AOCs would call the relevant FAA traffic manager in the ATC Systems Command Center and present desired routes for the day's flights. If the routes were not possible, the coordinator could query the reason and negotiate an alternate plan. Once the NRP was implemented, route requests were submitted by computer instead of phone contact; following

review, the traffic manager replied by computer (yes-accepted, or no-not accepted), eliminating the opportunity for the company's traffic manager to learn the constraints that led to acceptance or rejection of the routes.

5.2 Decision-Making Challenges in NextGen

5.2.1 Information overload

The technological capability to provide almost unlimited information to flight crews increases the possibility of information overload. Pilots will be challenged to define and access needed information in a timely manner, and to integrate information from several sources to create a coherent situation model. Depending on information design and display characteristics, the ability to pattern-match may be reduced, and more analytical processing may be required – with its attendant increase in cognitive demands..

5.2.2 Development of new expertise

In the early stages of NextGen, flight crews will be unfamiliar with new systems and procedures, and will need to develop expertise in the changed operational domain. The knowledge store that formed the basis for informed heuristics will need to be updated, and the use of shortcuts that work in current operations may lead to errors or mis-assessments in NextGen operations. For example, crews may use old models rather than new automation capabilities when judging the feasibility of a low-visibility CSMR approach, or may break out of a paired approach based on old standards of safe separation.

5.2.3 Overreliance on automation

Because so much of the flying task will be accomplished via automated systems, the tendency to rely on them in decision-making tasks may be exacerbated, especially under time pressure. Susceptibility to automation bias may increase. Flight crews will be dependent on automation for maintaining efficient TBO, and may be reluctant to question automation functioning or to make tactical interventions if it means this efficiency would be diminished.

5.2.4 Non-vigilance and fatigue

Extensive research has demonstrated that humans are not good at monitoring for long periods of time, and non-vigilance and complacency are certain to be challenges in the highly automated NextGen environment. Moreover, flight crews engaged in prolonged monitoring are likely to experience fatigue.

5.2.5 Erosion of skills

Dependence on automation will also serve to keep pilots out of the flying-task loop, fostering complacency and an erosion of flying and situation assessment skills. This may be the most critical challenge of NextGen operations – to ensure that flight crews maintain proficiency

so that they are prepared to take over from automation when needed. A test of NextGen operations will be how well they can accommodate anomalies and off-nominal events. Skilled flight crew response will be key.

Acknowledgements

This effort was funded by a grant to NASA Ames Research Center from the FAA Human Factors Research and Engineering Group, ATO-P, through FAA/NASA Interagency Agreement #DTFAWA-10-X-80005, Annex 9.

Portions of this report were previously published in the following works: Mosier (2002), Mosier & Fischer (2010), Orasanu, Martin & Davison (2001), Orasanu, Parke, Fischer, & McDonnell (2009). Acknowledgements to Research Assistant Stanton Mak for his assistance.

References

- Air Accidents Investigations Branch (AAIB) (1990). *Report on the accident to Boeing 737-400 G-OBME near Kegworth, Leicestershire on 8 January, 1989*. (Aircraft Accident Report 4/90). HMSO, London.
- Arrabito, G.R. (2009). Effects of talker sex and voice style of verbal cockpit warnings on performance. *Human Factors*, 51, 3-20.
- Barnett, B. & Wickens, C. D. (1986). *Non-optimality in the diagnosis of dynamic system states*. (Technical Report CPL_86-8). Champaign, IL: University of Illinois, Cognitive Psychophysiology Laboratory, Department of Psychology.
- Bass, E. J., & Pritchett, A. R. (2002). Human-automated judgment learning: a methodology to investigate human interaction with automated judges. In *Proceedings of the 46th Annual Meeting of the Human Factors and Ergonomics Society*. Baltimore, MD, Sept. 30-Oct. 4.
- Bearman, C., Paletz, S. B. F., Orasanu, J., & Brooks, B. P. (2009). Organizational pressures and mitigating strategies in Alaska aviation. *Aviation, Space and Environmental Medicine*, 80(12), 1055-1058.
- Bearman, C. R., Paletz, S. B. F., Orasanu, J., & Thomas, M. J. W. (2010). The breakdown of coordinated decision making in distributed systems. *Human Factors*, 52(2), 173-188.
- Beringer, D. G. (2000). Development of highway-in-the-sky displays for flight-path guidance: History, performance results, guidelines. *Proceedings of the IEA 2000/HFES 2000 Congress*, San Diego, CA.
- Billings, C. E. (1996). *Human-centered aviation automation: Principles and guidelines*. (NASA Technical Memorandum #110381) NASA Ames Research Center, Moffett Field, CA.
- Bisantz, A. & Pritchett, A. (2003). Measuring the fit between human judgments and automated alerting

- algorithms: A study of collision detection. *Human Factors*, 45(2), 266-280.
- Bisantz, A. M., Roth, E., Brickman, B., Gosbee, L. L., Hettinger, L., & McKinney, J. (2003). Integrating cognitive analyses in a large-scale system design process. *International Journal of Human-Computer Studies*, 58, 177-206.
- Bonnet, M. H., Balkin, T. J., Dinges, D. F., Roehrs, T., Rogers, N. L., & Wesensten, N. J. (2005). The use of stimulants to modify performance during sleep loss: A review by the Sleep Deprivation and Stimulant Task Force of the American Academy of Sleep Medicine. *Sleep*, 28, 1164-1187.
- Bowers, C. A., Jentsch, F., Salas, E., & Braun, C. C. (1998). Analyzing communication sequences for team training needs. *Human Factors*, 40, 672-679.
- Bowers, C. A., Oser, R. L., Salas, E., & Cannon-Bowers, J. A. (1996). Team performance in automated systems. In R. Parasuraman & M. Mouloua (Eds.), *Automation and human performance: Theory and applications* (pp. 243–263). Mahwah, NJ: Erlbaum.
- Bowers, C., Thornton, C., Braun, C., Morgan, B. B., and Salas, E. (1998). Automation, task difficulty, and aircrew performance. *Military Psychology*, 10(4), 259-274.
- Bronner, R. (1982). *Decision and Stress*. New York: Academic Press.
- Brunswik, E. (1943). Organismic achievement and environmental probability. *Psychological Review*, 50, 255–272.
- Brunswik, E. (1955). Representative design and probabilistic theory in a functional psychology. *Psychological Review*, 62, 193-217.
- Brunswik, E. (1956). *Perception and the representative design of psychological experiments*. Berkeley, CA: University of California Press.
- Cacioppo, J. T., Gardner, W. L., & Berntson, G. G. (1999). The affect system has parallel and integrative processing components: Form follows function. *Journal of Personality and Social Psychology*, 76, 839–855.
- Camasso, M. & Jagannathan, R. (2001.) Flying Personal Planes: Modeling the Airport Choices of General Aviation Pilots using Stated Preference Methodology. *Human Factors*, 43(3), 392-404.
- Cannon-Bowers, J. A., Salas, E., & Converse, S. A. (1993). Shared mental models in expert team decision making. In J. J. Castellan (Ed.), *Individual and group decision making: Current issues* (pp. 221-246). Hillsdale, NJ: LEA.
- Cellier, J., Eyrolle, H., & Marine, C. (1997). Expertise in dynamic environments. *Ergonomics*, 40, 28-50.
- Charness, N., & Tuffiash, M. (2008). The role of expertise research and human factors in capturing, explaining, and producing superior performance. *Human Factors*, 50(3) 427-432.
- Chi, M. T. H., Glaser, R., Farr, M. J. (1988). *The nature of expertise*. Hillsdale, NJ: Erlbaum Associates.
- Chi, M., Feltovich, P., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science*, 5, 121-152.

- Chi, M., Glaser, R., & Rees, E. (1982). Expertise in problem solving. In R.S. Steinberg (Ed.), *Advances in the psychology of human intelligence, Vol. 1* (pp. 7-75). Hillsdale, NJ: Lawrence Erlbaum Associates.
- Christoffersen, K., & Woods, D. (2002). How to make automated systems team players. *Advances in human performance and cognitive engineering research, Vol. 2* (pp. 1-12). New York: Elsevier Science.
- Cohen, M. (2011). Knowns, known unknowns, and unknown unknowns: Synergies between intuitive and deliberative approaches to time, uncertainty, and information. In K. L. Mosier & U. M. Fischer (Eds.), *Informed by knowledge: Expert performance in complex situations* (pp. 371-396). NY: Taylor & Francis.
- Cohen, M. S., Freeman, J. R., & Thompson, B. B. (1997). Training the naturalistic decision maker. In C. E. Zsombok, & G. Klein (1997). *Naturalistic decision making* (pp. 257-268). Mahwah, NJ: Lawrence Erlbaum Associates.
- Cohen, M., Freeman, J. T., & Wolf, S. (1996). Meta-recognition in time-stressed decision making: Recognizing, critiquing, and correcting. *Human Factors, 38*(2), 206-219.
- Cohen, M.S. (1993). Taking risk and taking advice: The role of experience in airline pilot diversion decisions. In R.S. Jensen & D. Neumeister (Eds.), *Proceedings of the Seventh International Symposium on Aviation Psychology* (pp. 244-247). Columbus, OH: Department of Aviation, The Ohio State University.
- Cohen, M.S., Adelman, L., Tolcott, M.A., Bresnick, T.A., & Marvin, F.F. (1993). *A cognitive framework for battlefield commanders' situation assessment* (Technical Report 93-1). Arlington, VA: Cognitive Technologies, Inc.
- Connolly, T. (1988). Hedge-clipping, tree-felling, and the management of ambiguity. In M. B. McCaskey, L. R. Pondy, & H. Thomas (Eds.), *Managing the challenge of ambiguity and change*. NY: Wiley.
- Cook, M. B., & Smallman, H. S. (2008). Human factors of the confirmation bias in intelligence analysis: Decision support from graphical evidence landscapes. *Human Factors, 50*(5), 745-754.
- Cosmides, L., & Tooby, J. (2000). Evolutionary psychology and the emotions. In M. Lewis & J. M. Haviland-Jones (Eds.), *Handbook of emotions* (2nd ed., pp. 91-115). New York: Guilford.
- Christoffersen, K., & Woods, D. (2002). How to make automated systems team players. *Advances in human performance and cognitive engineering research, Vol. 2* (pp. 1-12). New York: Elsevier Science.
- Cooke, N. J., Salas, E., Cannon-Bowers, J. A., & Stout, R. J. (2000). Measuring team knowledge. *Human Factors, 42*, 151-173.
- Costley, J., Johnson, D., and Lawson, D. (1989). A comparison of cockpit communication B737-B757. *Proceedings of 5th International Symposium on Aviation Psychology* (pp. 423-418). Columbus, OH: The Ohio State University.
- Cushing, S. (1994). *Fatal words: Communication clashes and aircraft crashes*. Chicago, IL: Chicago University Press.

- Cushing, S. (1997). *Fatal words: communication clashes and aircraft crashes*. Chicago, IL: University of Chicago Press.
- Damasio, A. (1994). *Descartes' error: Emotion, reason, and the human brain*. New York: Penguin Books.
- Damos, D., John, R. S., and Lyall, E. A. (2005). Pilot activities and level of cockpit automation. *The International Journal of Aviation Psychology*, 15(3), 251-268.
- Davies, M. F. (1997). Belief persistence after evidential discrediting: The impact of generated versus provided explanations on the likelihood of discredited outcomes. *Journal of Experimental Social Psychology*, 33, 561-578.
- Davison, J. & Fischer, U. (2003). When language becomes a barrier instead of a bridge: Communication failures between pilots and air traffic controllers. In R. Jensen (Ed.), *Proceedings of the 12th International Symposium on Aviation Psychology*. Dayton, OH.
- Dekker, S. (2005). *Ten questions about human error: A new view of human factors and system safety*. New York: Erlbaum (Taylor & Francis)
- Dekker, S. (2006). *The field guide to understanding human error*. Aldershot, England: Ashgate.
- Dekker, S., & Lützhöft, M. (2004). Correspondence, cognition and sense making: A radical empiricist view of situation awareness. In S. Banbury & S. Tremblay (Eds.), *A cognitive approach to situation awareness: Theory and application* (pp. 22-41). Aldershot, UK: Ashgate.
- Dekker, S., & Woods, D. D. (1999). Automation and its impact on human cognition. In S. Dekker & E. Hollnagel (Eds.), *Coping with computers in the cockpit* (pp. 7-27). Aldershot: Ashgate.
- Dijksterhuis, A., Bos, M. W., Nordgren, L. F., & van Baaren, R. B. (2006). On making the right choice: The deliberation-without-attention effect. *Science*, 311, 1005-1007.
- Dismukes, R.K (2010). Remembrance of things future: Prospective memory in laboratory, workplace, and everyday settings. In D.H. Harris (ed.), *Reviews of Human Factors and Ergonomics, Vol 6*. (pp. 79-122). Santa Monica CA: Human Factors and Ergonomics Society.
- Dismukes, R. K., Berman, B. A., & Loukopoulos, L. D. (2007). *The limits of expertise: Rethinking pilot error and the causes of airline accidents*. England: Ashgate.
- Dörner, D. (1992). *Die Logik des Mißlingens: Strategisches Denken in komplexen Situationen*. Hamburg: Rowohlt Taschenbuch Verlag.
- Dreyfus, H. L. (1997). Intuitive, deliberative, and calculative models of expert performance. In C. E. Zsombok & G. Klein (Eds.), *Naturalistic decision making* (pp. 17-28). New Jersey: Lawrence Erlbaum Associates.
- Driskell, J. E., Salas, E., & Johnston, J. (1999). Does stress lead to a loss of team perspective? *Group Dynamics: Theory, Research, and Practice*, 3(4), 291-302.
- Durso, F. T., & Gronlund, S. D. (1999). Situation awareness. In F. T. Durso (Ed.), *Handbook of applied cognition*. (pp. 283-314). New York, NY US: John Wiley & Sons Ltd.

- Durso, F. T., & Sethumadhavan, A. (2008). Situation awareness: Understanding dynamic environments. *Human Factors, 50*(3), 442-448.
- Durso, F. T., Rawson, K. A., & Giroto, S. (2007). Comprehension and situation awareness. In F. T. Durso, R. S. Nickerson, S. T. Dumais, S. Lewandowsky & T. J. Perfect (Eds.), *Handbook of applied cognition (2nd ed.)*. (pp. 164-193). Hoboken, NJ US: John Wiley & Sons Inc.
- Dyer, J. L. (1984). Team research and team training: A state-of-the-art review. In F. A. Muckler, A. S. Neal & L. Strother (Eds.), *Human factors review* (pp. 285-323). Santa Monica, CA.
- Einhorn, H. J. (1974). Expert judgment: Some necessary conditions and an example. *Journal of Applied Psychology, 59*(5), 562-571.
- Ellsworth, P. C., & Scherer, K. R. (2003). Appraisal processes in emotion. In R. J. Davidson, K. R. Scherer, & H. H. Goldsmith (Eds.), *Handbook of affective sciences* (pp. 572-595). New York: Oxford University Press.
- Endsley, M. R. (1988). Design and evaluation for situation awareness enhancement. In *Proceedings of the Human Factors Society 32nd Annual Meeting (Vol. 1)*, pp. 97-101. Santa Monica, CA: Human Factors Society.
- Endsley, M. R. (1995). A taxonomy of situation awareness errors. In R. Fuller, N. Johnston, & N. McDonald (Eds.), *Human factors in aviation operations* (pp. 287-292). Aldershot, England: Avebury Aviation, Ashgate. a
- Endsley, M. R. (1995). Toward a theory of situation awareness in dynamics systems. *Human Factors, 37*(1), 32-64. b
- Endsley, M. R. (1996). Automation and situation awareness. In R. Parasuraman, & M. Mouloua (Eds.), *Automation and human performance: Theory and applications* (pp. 163-181). New Jersey: Lawrence Erlbaum Associates.
- Endsley, M. R. (1999). Situation awareness in aviation systems. In D. J. Garland, J. A. Wise & V. D. Hopkin (Eds.), *Handbook of aviation human factors* (pp. 257-276). Mahwah, NJ: Erlbaum.
- Endsley, M. R. (2000). Theoretical underpinnings of situation awareness: A critical review. In M. R. Endsley & D. J. Garland (Eds.), *Situation awareness analysis and measurement* (pp. 3-32). Mahwah, NJ: Erlbaum.
- Endsley, M. R. (2004). Situation awareness: Progress and directions. In S. Banbury & S. Tremblay (Eds.), *A cognitive approach to situation awareness: Theory and application* (pp. 22-41). Aldershot, UK: Ashgate.
- Entin, E. E., & Serfaty, D. (1999). Adaptive team coordination. *Human Factors, 38*, 232-250.
- Espinosa, A., Lerch, J., Kraut, R. (2004). Explicit vs. implicit coordination mechanisms and task dependencies: One size does not fit all. In E. Salas and S. M. Fiore (Eds.), *Team cognition: Understanding the factors that drive process and performance*. (pp. 107-129). Washington, DC: American Psychological Association.
- FAA (1983). *Pilot's spatial disorientation (AC 60-4A)*. Washington, DC: Federal Aviation Administration.

- FAA (2009). *NextGen Mid-Term Concept of Operations for the National Airspace System, Version 1.0*. Washington, DC: FAA Air Traffic Organization NextGen& Operations Planning, Research & Technology Development, Air Traffic Systems Concept Development.
- Fischer, U., Davison, J., & Orasanu, J. (2003). What makes flight situations risky? Examining commercial and general aviation pilots' concepts of risk. In *Proceedings of the 12th International Symposium on Aviation Psychology* (pp. 380-384). Columbus, OH: The Ohio State University.
- Fischer, U., McDonnell, L., & Orasanu, J. (2007). Linguistic correlates of team performance: Toward a tool for monitoring team functioning during space missions. *Aviation, Space and Environmental Medicine*, 78(5), II, B86-95.
- Fischer U., & Orasanu, J. (2000). Error-challenging strategies: Their role in preventing and correcting errors. *Proceedings of the International Ergonomics Association 14th Triennial Congress and the Human Factors and Ergonomics Society 44th Annual Meeting, vol. 1* (pp. 30-33). Santa Monica, CA: Human Factors and Ergonomics Society.
- Fischer, U., Orasanu, J., & Davison, J. (2003). Why do pilots take risks? Some insights from a think-aloud study. In M. J. Cook (Ed.), *Proceedings of the Human Factors of Decision Making in Complex Systems Meeting* (pp. 44-46). Dundee, Scotland: University of Abertay.
- Fischer, U., Orasanu, J., & Montalvo, M. (1993). Efficient decision strategies on the flightdeck. *Proceedings of the 7th International Symposium on Aviation Psychology* (pp. 238-243). Columbus, OH: The Ohio State University.
- Fischer, U., Orasanu, J., & Wich M. (1995). Experts pilots' perceptions of problem situations. *Proceedings of the 8th International Symposium of Aviation Psychology*, 777-782.
- Fischhoff, B. (1975). Hindsight \neq foresight: The effect of outcome knowledge on judgment under uncertainty. *Journal of Experimental Psychology: Human Perception and Performance*, 1(3), 288-299.
- Fiske, S. T. & Taylor, S. E. (1991). *Social Cognition*, (2nd. Edn). New York: McGraw-Hill.
- Flin, R., Slaven, G. & Stewart, K. (1996). Emergency Decision Making in the Offshore Oil and Gas Industry. *Human Factors*, 38, 262-277.
- Funk, K. (1991). Cockpit task management: Preliminary definitions, normative theory, error taxonomy, and design recommendations. *International Journal of Aviation Psychology*, 1, 271-285.
- Galinsky, A.D. & Moskowitz, G. B. (2000). Counterfactuals as behavioral primes: Priming the simulation heuristic and consideration of alternatives. *Journal of Experimental Social Psychology*, 36, 384-409.
- Gawande, A., & Bates, D. (2000, February). The use of information technology in improving medical performance: Part I. Information systems for medical transactions. *Medscape General Medicine*, 2, 1-6.
- Gigerenzer, G. (2007). *Gut feelings: The intelligence of the unconscious*. New York: Penguin Books.

- Gigerenzer, G. (2008). Why heuristics work. *Perspectives on Psychological Science*, 3(1), 20-29.
- Gigerenzer, G., & Selten, R. (2001). *Bounded rationality: The adaptive toolbox*. Cambridge, MA: MIT Press.
- Ginnett, R. C. (1993). Crew as groups: Their formation and their leadership. In E. Weiner, B. Kanki & R. Helmreich (Eds.), *Cockpit resource management* (pp. 71-98). San Diego, CA: Academic Press.
- Goh, J., & Wiegmann, D. A. (2001). Visual flight rules flight (VFR) into adverse weather: An empirical investigation of the possible causes. *The International Journal of Aviation Psychology*, 11, 359-379.
- Hammond, K. R. (1993). Naturalistic decision making from a Brunswikian viewpoint: Its past, present, future. In G. A. Klein, J. Orasanu, R. Calderwood, & C. E. Zsombok (Eds.), *Decision making in action: Models and methods* (pp. 205-227). NJ: Ablex Publishing Co.
- Hammond, K. R. (1996). *Human judgment and social policy*. New York: Oxford Press.
- Hammond, K. R. (1999). Coherence and correspondence theories of judgment and decision making. In T. Connolly, H. R. Arkes, & K. R. Hammond (Eds.), *Judgment and decision making: An interdisciplinary reader* (pp. 53-65). NY: Cambridge University Press.
- Hammond, K. R. (2000). *Judgments under stress*. New York: Oxford Press.
- Hammond, K. R. (2007). *Beyond rationality: The search for wisdom in a troubled time*. NY: Oxford University Press.
- Hammond, K. R., & Stewart, T. R. (Eds.) (2001). *The essential Brunswik: Beginnings, explications, applications*. NY: Oxford University Press.
- Hammond, K. R., Hamm, R. M., Grassia, J., & Pearson, T. (1997). Direct comparison of the efficacy of intuitive and analytical cognition in expert judgment. In W. M. Goldstein & R. M. Hogarth (Eds.), *Research on judgment and decision making: Currents, connections, and controversies* (pp. 144-180). Cambridge: Cambridge University Press.
- Hammond, K. R., McClelland, G. H., & Mumpower, J. (1980). *Human judgment and decision making: Theories, methods, and procedures*. NY: Praeger.
- Harrison, Y., & Horne, J. A. (1997). Sleep deprivation affects speech. *Sleep*, 20, 871-878.
- Harrison, Y., & Horne, J. A. (2000). The impact of sleep deprivation on decision making: A review. *Journal of Experimental Psychology Applied*, 6(3), 236-249.
- Harville, D. L., Barnes, C., & Elliott, L. R. (2004). Team communication and performance during sustained command and control operations: Preliminary results (Interim Report). Brooks AFB, TX: Air Force Research Laboratory, Fatigue Countermeasures Branch.
- Hawkins, S. A., & Hastie, R. (1990). Hindsight: Biased judgments of past events. *Psychological Bulletin*, 107, 311-327.
- Hayashi, A. M. (2001). When to trust your gut. *Harvard Business Review*, 78, 59-65.
- Helmreich, R. L., & Foushee, C. H. (1993). Why Crew Resource Management? Empirical and theoretical bases of human factors training in aviation. In E. L. Wiener, B. G. Kanki, & R. L.

- Helmreich (Eds.), *Cockpit Resource Management* (pp. 3-45). San Diego, CA
- Helmreich, R. L., & Merritt, A. C. (1998). *Culture at work in aviation and medicine: National, organizational and professional influences*. England: Ashgate.
- Helmreich, R. L., & Sexton, J. B. (2004). Group interaction under threat and high workload. In R. Dietrich & T. M. Childress (Eds.), *Group interaction in high risk environments* (pp. 9-23). Burlington, VT: Ashgate.
- Hirt, E.R., Kardes, F.R. & Markman, K.D. (2003). Activating a mental simulation mind-set through generation of alternatives: Implications for debiasing in related and unrelated domains. *Journal of Experimental Social Psychology*, 40, 374-383.
- Holbrook, J. B., Orasanu, J., & McCoy, C. E. (2003). Weather-related decision making by aviators in Alaska, *12th International Symposium on Aviation Psychology*. Dayton, OH.
- Hooey, B. L., & Foyle, D. C., (2001). A post-hoc analysis of navigation errors during surface operations: Identification of contributing factors and mitigating solutions. Proceedings of the Eleventh International Symposium on Aviation Psychology. Columbus, OH: The Ohio State University.
- Jacobson, C., & Mosier, K. L. (2004). Coherence and correspondence decision making in aviation: A study of pilot incident reports. *International Journal of Applied Aviation Studies*, 4, 123-134.
- Jelalian, E., & Miller, A. G. (1984). The perseverance of beliefs: Conceptual perspectives and research developments. *Journal of Social and Clinical Psychology*, 2, 25-56.
- Johnston, N. (1996). Managing risk in flight operations. In: B. J. Hayward, & A. R. Lowe (Eds.), *Applied Aviation Psychology: Achievement, Change and Challenge* (pp. 1-19). Aldershot, England: Ashgate Publishing.
- Jones, D. G., & Endsley, M. R. (1996). Sources of situation awareness errors in aviation. *Aviation, Space, and Environmental Medicine*, 67(6), 507-512.
- Jones, D. G., & Endsley, M. R. (2000). Overcoming representational errors in complex environments. *Human Factors*, 42, 367-378.
- JPDO (Joint Planning and Development Office, 2007). *Concept of Operations for the Next Generation Air Transportation System, Version 2.0*.
- Kahneman, D., Slovic, P., & Tversky, A. (Eds.)(1982). *Judgment under uncertainty: Heuristics and biases*. Cambridge: Cambridge University Press.
- Kanki, B. G. (2010). Crew communication. In B. G. Kanki, R. L. Helmreich & J. Anca (Eds.), *Crew resource management, second edition*. San Diego: Academic Press.
- Kanki, B. G., Lozito, S., & Foushee, H. C. (1989). Communication indices of crew coordination. *Aviation, Space, and Environmental Medicine*, 60, 56-60.
- Keeney, R. L., & Raiffa, H. (1976). *Decisions with multiple objectives: Preferences and value tradeoffs*. Cambridge: Cambridge University Press.
- Keinan, G. (1987). Decision making under stress: Scanning of alternatives under controllable and

- uncontrollable threats. *Journal of Personality and Social Psychology*, 52, 639-644.
- Kerstholt, J. H. (1994). The effect of time pressure on decision making behavior in a dynamic task environment. *Acta Psychologica*, 86, 89-104.
- Kerstholt, J., Pssenier, P., Houttuin, K. & Schuffel H. (1996.) The Effect of a Priori Probability and complexity on Decision Making in a Supervisory Control Task. *Human Factors*, 38, 65-78.
- Khoo, Y.-L., & Mosier, K. L. (2008). The impact of time pressure and experience on information search and decision-making. *Journal of Cognitive Engineering and Decision Making*, 2, 275-294.
- Kirlik, A. & Bertel, S. (2009). Decision making under pressure and constraints: Bounded rationality. In J.J. Cochran (Ed.), *Wiley Encyclopedia of Operations Research and Management Science*. New York: Wiley.
- Klein, G. A. (1989). Recognition-primed decisions. In W. B. Rouse (Ed.), *Advances in Man-Machine System Research, Volume 5* (pp. 47-92). Greenwich, CT: JAI Press.
- Klein, G. (1993a). Recognition-primed decision (RPD) model of rapid decision making. In G. A. Klein, J. Orasanu, R. Calderwood & C. Zsombok (Eds.), *Decision making in action: Models and methods* (pp. 103-147). Norwood, NJ: Ablex.
- Klein, G. (1993b). *Naturalistic decision making: Implications for design*. CSERIAC SOAR Report 93-1. Ohio: Wright Patterson Air Force Base.
- Klein, G. (2000). Analysis of situation awareness from critical incident reports. In M. R. Endsley & D. J. Garland (Eds.), *Situation awareness, analysis, and measurement* (pp. 51-71). Mahwah, NJ: Erlbaum.
- Klein, G. A. (2003). *Intuition at work: Why developing your gut instincts will make you better at what you do*. NY: Doubleday.
- Klein, G. (2008). Naturalistic decision making. *Human Factors*, 50(3), 456-460.
- Klein, G. A., Calderwood, R., & Clinton-Cirocco, A. (1986). *Rapid decision making on the fire ground* (KA-TR-84-41-7). Yellow Springs, OH: Klein Associates Inc. (Prepared under contract MDA903-85-G-0099 for the U.S. Army Research Institute, Alexandria, VA)
- Klein, G. A., Ross, K. G., Moon, B. M., Klein, D. E., Hoffman, R. R., & Hollnagel, E. (2003). Macrocognition. *IEEE Intelligent systems*, 18(3), 81-85.
- Klein, G., Woods, D. D., Bradshaw, J. M., Hoffman, R. R., & Feltovich, P. J. (2005). Ten challenges for making automation a 'team player' in joint human-agent activity. *Intelligent Systems, IEEE*, 19(6), 91-95.
- Klimoski, R. J., & Mohammed, S. (1994). Team mental model: Construct or metaphor? *Journal of Management*, 20, 403-437.
- Layton, C., Smith, P. J., & McCoy, C. E. (1994). Design of a cooperative problem-solving system for en-route flight planning: An empirical evaluation. *Human Factors*, 36, 94-119.
- Lerner, J. S., & Keltner, D. (2001). Fear, anger, and risk. *Journal of Personality and Social Psychology*, 81, 146-159.

- Lerner, S., & Tiedens, Z. (2006). Portrait of the angry decision maker: How appraisal tendencies shape anger's influence on cognition. *Journal of Behavioral Decision Making*, *19*, 115–137.
- Lichtenstein, S., & Fischhoff, B. (1977). Do those who know more also know more about how much they know? The calibration of probability judgements. *Organizational Behavior and Human Performance*, *20*, 159-183.
- Lieberman, P., Morey, A., Hochstadt, J. E., Larson, M., & Mather, S. (2005). Mount Everest: A space-analog for speech monitoring of cognitive deficits and stress. *Aviation Space & Environmental Medicine*, *76*(6), B198-207.
- Lilienfeld, S. O., Ammirati, R. & Landfield, K. (2009). Giving debiasing away: Can psychological research on correcting cognitive errors promote human welfare? *Perspectives on Psychological Science*, *4*, 390-398.
- Linde, C. (1988). The quantitative study of communicative success: Politeness and accidents in aviation discourse. *Language in Society*, *17*, 375-399.
- Lipshitz, R. & Ben Shaul, O. (1997). Schemata and mental models in recognition- primed decision making. In C. Zsombok & G. Klein (Eds.), *Naturalistic decision making* (pp. 293-303). Hillsdale, NJ: Erlbaum.
- Lipshitz, R. (1993). Converging themes in the study of decision-making in realistic settings. In G. A. Klein, J. Orasanu, R. Calderwood, & C. E Zsombok (Eds.), *Decision making in action: Models and methods* (pp. 103-137). NJ: Ablex Publishing Corp.
- Lipshitz, R. (1997). Naturalistic decision making perspectives on decision errors. In C. Zsombok & G. Klein (Eds.), *Naturalistic decision making* (pp. 151-162). Mahwah, NJ: Erlbaum.
- Lipshitz, R., & Strauss, O. (1997). Coping with uncertainty: A naturalistic decision making analysis. *Organizational Behavior and Human Decision Processes*, *69*, 149-163.
- Lipshitz, R., Klein, G., Orasanu, J., & Salas, E. (2001). Taking stock of Naturalistic Decision Making. *Journal of Behavioral Decision Making*, *14*, 331–352.
- Loewenstein, G. F., & Lerner, J. S. (2003). The role of affect in decision making. In R. J. Davidson, K. R. Scherer, & H. H. Goldsmith (Eds.), *Handbook of affective sciences* (pp. 619–642). New York: Oxford University Press.
- Loukopoulos, L. D., Dismukes, R. K., & Barshi, E. (2003). Concurrent task demands in the cockpit: Challenges and vulnerabilities in routine flight operations. *Proceedings of the 12th International Symposium on Aviation Psychology* (pp. 737-742). Dayton, OH: The Wright State University.
- Luce, M. F., Bettman, J. R., & Payne, J. W. (1997). Choice processing in emotionally difficult decisions. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *23*, 384–405.
- Lyons, T., Ercoline, W., O'Toole, K., & Grayson, K. (2006). Aircraft and related factors in crashes involving spatial disorientation: 15 years of U.S. Air Force data. *Aviation, Space, and Environmental Medicine*, *77*(7), 720-723.
- Mackenzie, C.F., Horst, R.L., Mahaffey, D.L. et al. (1993). Group decision making during trauma

- patient resuscitation and anesthesia. *Proceedings of the 37th Annual Meeting of the Human Factors and Ergonomics Society*. Santa Monica, CA: Human Factors and Ergonomics Society.
- Maher, J. W. (1989). Beyond CRM to decisional heuristics: An airline generated model to examine accidents and incidents caused by crew errors in deciding. In R. S. Jensen (Ed.), *Proceedings of the 5th International Symposium on Aviation Psychology* (pp. 439-444). Columbus, OH: The Ohio State University
- Mallis, M. M., Banks, S., & Dinges, D. F. (2010). Aircrew fatigue, sleep need and circadian rhythmicity. In E. Salas & D. Maurino (Eds.), *Human factors in aviation, 2nd Edition*. Oxford, UK: Elsevier.
- Manzey, D., Reichenbach, J., & Onnasch, L. (2009). Human performance consequences of automated decision aids in states of fatigue. *Proceedings of the Human Factors and Ergonomics Society 53rd Annual Meeting* (pp. 329-333). Santa Monica, CA: HFES.
- Maule, J. (2009). Can computers help overcome limitations in human decision making? *Proceedings of NDM9, the 9th International Conference on Naturalistic Decision Making*. London, UK: British Computer Society.
- Maule, A. J. & Hockey, G. R. (1993). State, stress and time pressure. In O. Svenson and J. Maule (Eds.), *Time pressure and stress in human judgment and decision making* (pp. 83-239). New York: Plenum.
- McKinney, E., Jr. (1993). Flight leads and crisis decision-making. *Aviation, Space & Environmental Medicine*, 64 (5), 359-362.
- Mearns, K. J., & Flin, R. (2001). Assessing the state of organizational safety – Culture or climate? In H. Ellis & N. Macrae (Eds.), *Validation in psychology*. London: Transaction Publishers.
- Mearns, K., Flin, R., Gordon, R., & Fleming, M. (2001). Human and organizational factors in offshore safety. *Work & Stress*, 15(2), 144-160.
- Morrow, D. G., Soederberg Miller, L. M., Ridolfo, H. E., Magnor, C., Fischer, U. M., Kokayeff, N. K., Stine-Morrow, E. A. L. (2009). Expertise and age differences in pilot decision making. *Aging, Neuropsychology, and Cognition*, 16(1), 33–55.
- Mosier, K. L. (2002). Automation and cognition: Maintaining coherence in the electronic cockpit. In E. Salas (Ed.), *Advances in Human Performance and Cognitive Engineering Research, Volume 2* (pp. 93-121). Elsevier Science Ltd.
- Mosier, K. L. (2008). Technology and “naturalistic” decision making: Myths and realities. In J. M. C. Schraagen, L. Militello, T. Ormerod, & R. Lipshitz (Eds.) *Naturalistic decision making and macrocognition* (pp. 41-54). Aldershot, UK: Ashgate Publishing Limited.
- Mosier, K. L. (2009). Searching for Coherence in a Correspondence World. *Judgment and Decision Making* (4), 2, 154-163.
- Mosier, K. L., & Chidester, T. R. (1991). Situation assessment and situation awareness in a team setting. *Designing for Everyone: Proceedings of the 11th Congress of the International Ergonomics*
-

Association (pp. 798-800). Paris, 15-20 July

- Mosier, K., & Fischer, U. (2010). Judgment and decision making by individuals and teams: Issues, models, and applications. In D. Harris (Ed.), *Reviews of Human Factors and Ergonomics, Volume 6* (pp. 198-256). Santa Monica, CA: Human Factors and Ergonomics Society.
- Mosier, K. L., Rettenmaier, P., McDearmid, M., Ng, S., Wilson, J., Mak, S., & Orasanu, J. (2009). *Effects of operator state on pilot/ATC conflict*. Paper presented at the 9th International Conference on Naturalistic Decision Making, London, June 23–26.
- Mosier, K., Sethi, N, McCauley, S., Khoo, L., & Orasanu, J. (2007). What You Don't Know CAN Hurt You: Factors Impacting Diagnosis in the Automated Cockpit. *Human Factors*, 49, 300-310.
- Mosier, K. L., & Skitka, L. J. (1996). Human decision makers and automated aids: Made for each other? In R. Parasuraman, & M. Mouloua (Eds.), *Automation and human performance: Theory and applications* (pp. 201-220). New Jersey: Lawrence Erlbaum Associates.
- Mosier, K. L., Skitka, L. J., Dunbar, M., & McDonnell, L. (2001). Air crews and automation bias: The advantages of teamwork? *International Journal of Aviation Psychology*, 11, 1-14.
- Mosier, K. L., Skitka, L. J., Heers, S., & Burdick, M. D. (1998). Automation bias: Decision making and performance in high-tech cockpits. *International Journal of Aviation Psychology*, 8, 47-63.
- Mosier-O'Neill, K. (1989). A contextual analysis of pilot decision making. In R.S. Jensen (Ed.) *Proceedings of the Fifth International Symposium on Aviation Psychology* (pp. 371-376). Columbus: The Ohio State University.
- Muthard, E. K., & Wickens, C. D. (2002). Change detection after preliminary flight decisions: Linking planning errors to biases in plan monitoring. *Proceedings of the Human Factors and Ergonomics Society 46th Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.
- Nagel, D. (1988). Human error in aviation operations. In E. Weiner & D. Nagel (Eds.), *Human Factors in Aviation* (pp. 263-303). San Diego, CA: Academic Press.
- Naikar, N., Moylan, A., & Pearce, B. (2006). Analysing activity in complex systems with cognitive work analysis: Concepts, guidelines and case study for control task analysis. *Theoretical Issues in Ergonomics Science*, 7(4), 372-394.
- Nance, J. J. (1984). *Splash of colors: The self-destruction of Braniff International*. NY: William Morrow and Co.
- National Transportation Safety Board (NTSB). (1990). *United Airlines Flight 232, McDonnell Douglas DC-10-10 Sioux Gateway Airport, Sioux City, IA, July 19, 1989* (No. PB90-910406, NTSB/AAR-90/06). Washington, DC: National Transportation Safety Board.
- National Transportation Safety Board (NTSB) (1982). *Aircraft Accident Report: Air Florida, Inc., Boeing 737-222, N62AF, Collision with 14th Street Bridge, Near Washington National Airport, Washington, D. C., January 13, 1982* (NTSB-AAR-82-8). Washington, DC: Author.
- National Transportation Safety Board (NTSB) (1994). *Safety study: A review of flightcrew-involved, major accidents of U.S. air carriers, 1978 through 1990* (NTSB/SS-94/01). Washington DC: National Technical Information Service.

- Nemeth, C., Nunnally, M., O'Connor, M., Klock, P. A., & Cook, R. (2005). Making information technology a team player in safety: The case of infusion devices. In K. Henriksen, J. B. Battles, E.S. Marks, et al. (Eds.). *Advances in patient safety: From research to implementation (Volume 1: Research Findings)*. Rockville (MD): [Agency for Healthcare Research and Quality](#).
- Neri, D. F., Oyung, R. L., Colletti, L. M., Mallis, M. M., Tam, P. Y., & Dinges, D. F. (2002). Controlled breaks as a fatigue countermeasure on the flight deck. *Aviation, Space and Environmental Medicine*, *73*, 654-664.
- Newman, D. G. (2007). An overview of spatial disorientation as a factor in aviation accidents and incidents. *ATSB Transport Safety Investigation Report – B2007/0063*. Australia: Australian Transport Safety Board.
- Nikolic, M. I., Orr, J. M., & Sarter, N. B. (2004). Why pilots miss the green box? How display context undermines attention capture. *International Journal of Aviation Psychology*, *14*, 39-52.
- O'Hare, D. (2003). Aeronautical decision making: Metaphors, models, and methods. In P. S. Tsang & M. A. Vidulich (Eds.), *Principles and practice of aviation psychology* (pp. 201-238). Mahwah, NJ: Lawrence Erlbaum.
- O'Hare, D., & Smitheram, T. (1995). "Pressing on" into deteriorating conditions: An application of behavioral decision theory to pilot decision making. *International Journal of Aviation Psychology*, *5*, 351-370.
- O'Hare, D., & Wiggins, M. (2004). Remembrance of cases past: who remembers what, when confronting critical flight events? *Human Factors*, *46*, 277-287.
- Ochsner, K. N., & Gross, J. J. (2005). The cognitive control of emotion. *Trends in Cognitive Science*, *9*, 242-249.
- Ochsner, K. N., Ray, R. R., Hughes, B., McRae, K., Cooper, J. C., Weber, J., Gabrieli, J. D. E., & Gross, J. J. (2009). Bottom-up and top-down processes in emotion generation: Common and distinct neural mechanisms. *Psychological Science*, *20*, 1322-1331.
- Olshavsky, R. W. (1979). Task complexity and contingent processing in decision making: A replication and extension. *Organizational Behavior and Human Performance*, *24*, 300-316.
- Orasanu, J. (1990). *Shared mental models and crew decision making*. Technical Report No. 46. Princeton, NJ: Princeton University, Cognitive Science Laboratory.
- Orasanu, J. (1993). Decision making in the cockpit. In E. Wiener, B. Kanki, & R. Helmreich, (Eds.). *Cockpit Resource Management* (pp. 137-172). San Diego, CA: Academic Press.
- Orasanu, J. (1994). Shared problem models and flight crew performance. In N. Johnston, N. McDonald, & R. Fuller (Eds.), *Aviation psychology in practice* (pp. 255-285). Aldershot, UK: Ashgate Publishing.
- Orasanu, J. (1997). Stress and naturalistic decision making: Strengthening the weak links. In R. Flin, E. Salas, M. Strub & L. Martin (Eds.), *Decision making under stress; emerging themes and applications* (pp. 49-160). Aldershot, UK: Ashgate.

- Orasanu, J. (2010). Flight crew decision making. In B. G. Kanki, R. L. Helmreich & J. Anca (Eds.), *Crew resource management, second edition* (pp. 147-179). San Diego: Academic Press.
- Orasanu, J., & Connolly, T. (1993). The reinvention of decision making. In G. A. Klein, J. Orasanu, R. Calderwood, & C. E. Zsombok (Eds.). *Decision making in action: Models and methods* (pp. 3–20). Norwood, NJ: Ablex.
- Orasanu, J., Dismukes, R. K., & Fischer, U. (1993). Decision errors in the cockpit. *Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting* (pp. 363-367). Santa Monica, CA: Human Factors and Ergonomics Society.
- Orasanu, J., & Fischer, U. (1992). Distributed cognition in the cockpit: Linguistic control of shared problem solving, *Proceedings of the Fourteenth Annual Conference of the Cognitive Science Society* (pp. 189-194). Hillsdale, NJ: Erlbaum.
- Orasanu, J., & Fischer, U. (1997). Finding decisions in natural environments: The view from the cockpit. In C. Zsombok & G. Klein (Eds.), *Naturalistic decision making* (pp. 343-357). Hillsdale, NJ: Erlbaum.
- Orasanu, J., Fischer, U., & Tarrel, R. J. (1993). A taxonomy of decision problems on the flight deck. In R. S. Jensen & D. Neumeister (Eds.), *Seventh International Symposium on Aviation Psychology* (Vol. 1, pp. 226-232). Columbus, OH: Ohio State University.
- Orasanu, J., Fischer, U., & Davison, J. (2004). Risk perception and risk management in aviation. In: R. Dietrich, K. Jochum (Eds.), *Teaming up: Components of safety under high risk* (pp. 93-116). Aldershot, UK: Ashgate.
- Orasanu, J., Fischer, U., McDonnell, L. K., Davison, J., Haars, K. E., Villeda, E. & vanAken, C. (1998). How do flight crews detect and prevent errors? Findings from a flight simulation study. *Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting*, Chicago, IL, Vol. 1, 191-195.
- Orasanu, J., Martin, L., & Davison, J. (2001). Cognitive and contextual factors in aviation accidents: Decision errors. In E. Salas & G. Klein (Eds.), *Linking expertise and naturalistic decision making* (pp. 209-225). Mahwah, NJ: Erlbaum.
- Orasanu, J., Parke, B., Fischer, U., & McDonnell, L. (2009). *Crew coordination and collaboration, Ch. 5.8, Human Integration Design Handbook*. Houston, TX: NASA Johnson Space Center.
- Orasanu, J., & Strauch, B. (1994). Temporal factors in aviation decision making. In: L. Smith (Ed.), *Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting, vol. 2.* (pp. 935-929). Santa Monica, CA: Human Factors and Ergonomics Society.
- Parasuraman, R. (2000). Designing automation for human use: Empirical studies and quantitative models. *Ergonomics* (43), 931-951.
- Parasuraman, R. & Manzey, D. H. (2010). Complacency and bias in human use of automation: An attentional integration. *Human Factors*, 52, 381-410.
- Parasuraman, R., Molloy, R., & Singh, I. L. (1993). Performance consequences of automation-induced “complacency.” *International Journal of Aviation Psychology*, 3, 1-23.
- Parasuraman, R., & Riley, V. (1997). Humans and automation: Use, misuse, disuse, abuse. *Human*

Factors, 39, 230-253.

- Parke, B., Kanki, B. G., McCann, R. S., & Hooey, B. L. (1999). The effects of advanced navigation aids on crew roles and communication in ground taxi. *Proceedings of the 10th International Symposium on Aviation Psychology* (pp. 804-809). Columbus, OH: The Ohio State University.
- Parke, B., Kanki, B. G., Munro, P. A., Patankar, K., Renfro, D. F., Hooey, B. L., & Foyle, D. C. (2001). *The effects of advanced navigation aids and different ATC environments on task-management and communication in low visibility landing and taxi*. Paper presented at the 11th International Symposium on Aviation Psychology. Columbus, OH.
- Patel, V.L., & Groen, G.J. (1991). The general and specific nature of medical expertise: A critical look. In K.A. Ericsson & J. Smith (Eds.), *Toward a general theory of expertise: Prospects and limits* (pp. 93-125). Cambridge: Cambridge University Press.
- Payne, J. W. (1976). Task complexity and contingent processing in decision making: An information search and protocol analysis. *Organizational Behavior and Human Performance*, 16, 366-387.
- Payne, J. W., Bettman, J. R. & Johnson, E. J. (1988). Adaptive strategy selection in decision making. *Journal of Experimental Psychology: Learning, Memory and Cognition*, 14, 534-552.
- Perrin, B. M., Barnett, B. J., Walrath, L., & Grossman, J. D. (2001). Information order and outcome framing: An assessment of judgment bias in a naturalistic decision-making context. *Human Factors*, 43, 227-238.
- Peters, E., Västfjäll, D., Gärling, T., & Slovic, P. (2006). The role of affect in decision-making. A hot topic. *Journal of Behavioral Decision Making*, 19(2), 79-85.
- Phelps, E. A. (2006). Emotion and cognition: Insights from studies of the human amygdala. *Annual Review of Psychology*, 57, 27-53.
- Pilcher, J. J., McClelland, L. E., Moore, D. W., Haarmaan, H., Baron, J., Wallsten, T. S., et al. (2007). Language performance under sustained work and sleep deprivation conditions. *Aviation, Space and Environmental Medicine*, 78(5, Section II), B25-B38.
- Plat, M., & Amalberti, R. (2000). Experimental crew training to deal with automation surprises. In N. B. Sarter & R. Amalberti (Eds.), *Cognitive engineering in the aviation domain*. Mahwah, NJ: Lawrence Erlbaum Associates. (pp. 287-307).
- Prinzel, L. J. III (2003). *Team-centered perspective for adaptive automation design*. NASA /TM-2003-212154. Hampton, VA: National Aeronautics and Space Administration.
- Raby, M., & Wickens, C. D. (1994). Strategic workload management and decision biases in aviation. *International Journal of Aviation Psychology*, 4, 211-240.
- Rasmussen, J. (1976). Outlines of a hybrid model of the process plant operator. In T. B. Sheridan & G. Johanssen (Eds.), *Monitoring behavior and supervisory control* (pp. 371-384). NY: Plenum Press.
- Rasmussen, J. (1997). Merging paradigms: Decision making, management, and cognitive control. In R. Flin, E. Salas, M. Strub, & L. Martin (Eds.), *Decision making under stress: Emerging themes and applications* (pp. 67-81). Aldershot, UK: Ashgate.

- Reason, J. T. (1990). *Human Error*. Cambridge, UK: Cambridge University Press.
- Reason, J. T. (1997). *Managing the risks of organizational accidents*. Aldershot, England: Ashgate.
- Rodgers, M., Mogford, R. H., & Strauch, B. (2000). Post hoc assessment of situation awareness in air traffic control accidents and major aircraft accidents. In M. R. Endsley & D. J. Garland (Eds.), *Situation awareness, analysis, and measurement* (pp. 75-112). Mahwah, NJ: Erlbaum.
- Rosekind, M. R., Graeber, R. C., Dinges, D. F., Connell, L. J., Rountree, M. S., Spinweber, C. L., & Gillen, K. A. (1994). *Crew factors in flight operations IX: Effects of planned cockpit rest on crew performance and alertness in long-haul operations*. Moffett field, CA: NASA Ames Research Center.
- Rouse, W. B., Cannon-Bowers, J. A., & Salas, E. (1992). The role of mental models in team performance in complex systems. *IEEE Transactions on Systems, Man, and Cybernetics*, 22(6), 1296-1308.
- Sanna, L.J. & Schwarz, N. (2002). Debiasing the hindsight bias: The role of accessibility experiences and (mis)attributions. *Journal of Experimental Social Psychology*, 39, 287-295.
- Sanna, L. J., Schwarz, N. & Stocker, S. L. (2002). When debiasing backfires: Accessible content and accessibility experiences in debiasing hindsight. *Journal of Experimental Psychology*, 28, 497-502.
- Sarter, N. B. (1995). "Knowing when to look where": Attentional location on advanced automated flight decks. *Proceedings of the 8th International Symposium on Aviation Psychology* (Vol.1, pp. 239–242). Columbus: OH: The Ohio State University.
- Sarter, N. B. (2000). The need for multisensory feedback in support of effective attention allocation in highly dynamic event-driven environments: The case of cockpit automation. *International Journal of Aviation Psychology*, 10, 231–245.
- Sarter, N., & Schroeder, B. (2001). Supporting Decision Making and Action Selection under Time Pressure and Uncertainty: The Case of In-Flight Icing. *Human Factors*, 43(4) 573-583.
- Sarter, N. B., & Woods, D. D. (1994a). Pilot interaction with cockpit automation II: An experimental study of pilots' model and awareness of the flight management system. *International Journal of Aviation Psychology*, 4, 1-28.
- Sarter, N. R., & Woods, D. D. (1994b). Decomposing automation: Autonomy, authority, observability and perceived animacy. In M. Mouloua & R. Parasuraman (Eds.), *Human performance in automated systems: Current research and trends* (pp. 22-27). NJ: Lawrence Erlbaum Associates.
- Sarter, N B., Woods, D. D., & Billings, C. (1997). Automation surprises. In G. Savendy (Ed.), *Handbook of human factors/ergonomics, 2nd Edition*, (pp. 1926-1943). New York: Wiley.
- Schuch, H.P. (1992). The influence of flight experience on midair collision risk perception. *Accident Analysis & Prevention*, 24, 655-660.
- Segal, L. & Jobe, K. (1995). On the use of visual activity communication in the cockpit. *Proceedings of the 8th International Symposium on Aviation Psychology* (Vol.1, pp. 712-717). Columbus, OH: The Ohio State University.

- Serfaty, D., Entin, E. E., & Volpe, C. (1993). Adaptation to stress in team decision making and coordination. In *Proceedings of the Human Factors and Ergonomics Society, 37th Annual Meeting* (pp. 1228-1232). Santa Monica, CA: Human Factors and Ergonomics Society.
- Serfaty, D., MacMillan, J., Entin, E. E., & Entin, E. B. (1997). The decision making expertise of battle commanders. . In C. Zsombok & G. Klein (Eds.), *Naturalistic decision making* (pp. 233-246). Hillsdale, NJ: Erlbaum.
- Shappell, S., Detwiler, C., Holcomb, K., Hackworth, C., Boquet, A., & Wiegmann, D. A. (2007). Human error and commercial aviation accidents: An analysis using the human factors analysis and classification system. *Human Factors, 49*(2), 227-242.
- Sheridan, T. B., & Thompson, J. M. (1994). People versus computers in medicine. In M. S. Bogner (Ed.), *Human error in medicine* (pp. 141-158). NJ: Lawrence Erlbaum Associates.
- Sherry, L., Feary, M., Polson, P., & Palmer, E. (2001). What's it doing now?: Taking the covers off autopilot behavior. *Proceedings of the 11th International Symposium on Aviation Psychology*. Columbus, OH. (a)
- Sherry, L., Feary, M., Polson, P., Mumaw, R., & Palmer, E. (2001). *A cognitive engineering analysis of the vertical navigation (VNAV) function*. NASA /TM-2001-210915. Moffett Field, CA: Ames Research Center. (b)
- Silberstein, D., & Dietrich, R. (2003). Cockpit communication under high cognitive workload. In R. Dietrich, T. von Meltzer. *Communication in high risk environments. Linguistische Berichte. Sonderheft 12* (pp. 9-56). Hamburg: Helmut Buske Verlag.
- Simon, H. A. (1983). Alternative visions of rationality. In *Reason in human affairs*. Stanford, CA: Stanford University Press. [Chapter reprinted in H. R. Arkes & K. R. Hammond (Eds.) (1986), *Judgment and decision making: An interdisciplinary reader*. Cambridge: Cambridge University Press.]
- Simon, H. A., & Chase, W. G. (1973). Skill in chess. *American Scientist, 61*, 394-403.
- Simons, D. J. (2000). Current approaches to change blindness. *Visual Cognition, 7*, 1-15.
- Skitka, L. J., Mosier, K. L., & Burdick, M. (2000). Accountability and automation bias. *International Journal of Human-Computer Studies, 52*, 701-717.
- Sklar, A. E., & Sarter, N. B. (1999). Good Vibrations: Tactile Feedback in Support of Attention Allocation and Human-Automation Coordination in Event-Driven Domains. *Human Factors (41)*, 543-552.
- Slovic, P. (1987). The perception of risk. *Science, 236*, 280-285.
- Stanton, N. (1994). *Human factors of alarm design*. London: Taylor & Francis.
- Steiner, I. D. (1972). *Group processes and productivity*. New York, NY: Academic Press.
- Strauss, R., & Kirlik, A. (2006). Situation awareness as judgment II: Experimental demonstration. *International Journal of Industrial Ergonomics, 36*, 475-484.

- Stokes, A., Belger, A., & Zhang, K. (1990). *Investigation of factors comprising a model of pilot decision making: Part II. Anxiety and cognitive strategies in expert and novice aviators.* (Technical Report ARL-93-1/INEL-93-1). Savoy, IL: University of Illinois, Aviation Research Laboratory.
- Stokes, A. F., Pharmed, J. A., Kite, K. (1997). Stress effects upon communication in distributed teams. *IEEE International Conference on Systems, Man, and Cybernetics*, 5, 4171-4176. 12-15 Oct 1997.
- Tilley, A., & Warren, P. (1984). Retrieval from semantic memory during a night without sleep. *The Quarterly Journal of Experimental Psychology: Human experimental psychology*, 36A, 281-289.
- Tversky, A., & Kahneman, D. (1974). Judgment under uncertainty: Heuristics and biases. *Science*, 185, 1123-1124.
- Tversky, A., & Kahneman, D. (1981). The framing of decisions and the psychology of choice. *Science*, 211, 453-458.
- Vicente, K. J. (1990). Coherence- and correspondence-driven work domains: Implications for systems design. *Behavior and Information Technology*, 9(6), 493-502.
- Vicente, K. J. (1999). *Cognitive work analysis: Toward safe, productive, and health computer-based work.* Mahwah, NJ: Lawrence Erlbaum Associates.
- Vicente, K. J., & Pawlak, S. (1994). *Cognitive Work Analysis for the DURESS II System.* CEL 94-03, Cognitive Engineering Laboratory, University of Toronto, Toronto, Canada.
- Veinott, E. S., & Irwin, C. M. (1993). Analysis of communication in the standard versus automated aircraft. *Proceedings of the 7th International Symposium on Aviation Psychology* (pp. 584-588). Columbus, OH: The Ohio State University.
- Waag, W., & Bell, H. (1997). Situation assessment and decision-making in skilled fighter pilots. In C. E. Zsombok & G. Klein (Eds.), *Naturalistic decision making* (pp. 247-354). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.
- Wegwarth, O., Gaissmaier, W., & Gigerenzer, G. (2009). Smart strategies for doctors and doctors-in-training: Heuristics in medicine. *Medical Education*, 43, 721-728.
- Weick, K. E. (1995). *Sensemaking in organizations.* CA: Sage.
- Wickens, C. D. (2002). Situation awareness and workload in aviation. *Current Directions in Psychological Science*, 11(4), 128-133.
- Wickens, C. D. (2003). The when and how of using 2-D and 3-D displays for operational tasks. *Proceedings of the Annual Meeting of the Human Factors and Ergonomics Society* (pp. 403-406). Santa Monica, CA: Human Factors and Ergonomics Society.
- Wickens, C. D. & Flach, J. M. (1988). Information processing. In E. L. Wiener & D. C. Nagel (Eds.), *Human factors in aviation.* San Diego, CA: Academic Press (pp. 110-156).
- Wickens, C.D, Muthard, E.K., Alexander, A.L., van Offlen, P.J., & Podczerwinski, E.S. (2003). The influences of display highlighting and eccentricity for aviation surveillance. *Proceedings of the 47th Human Factors and Ergonomics Society.* Santa Monica, CA: Human Factors and Ergonomics Society.

- Wickens, C. D., Stokes, A. F., Barnett, B., & Hyman, F. (1988). Stress and pilot judgment: An empirical study using MIDIS, a microcomputer-based simulation. *Proceedings of the 32nd Annual Meeting of the Human Factors Society* (pp. 173-177). Santa Monica, CA: Human Factors and Ergonomics Society.
- Wickens, C. D., Stokes, A., Barnett, B., & Hyman, F. (1993). The effects of stress on pilot judgment in a MIDIS simulator. In O. Svenson & A. J. Maule (Eds.), *Time pressure and stress in human judgment and decision making*. (pp. 271-292). New York, NY US: Plenum Press.
- Wiener, E. L. (1989). *Human factors of advanced technology ("glass cockpit") transport aircraft*. (NASA Contractor Report No. 177528). Moffett Field, CA: NASA Ames Research Center.
- Wiggins, M. W., & Bollwerk, S. (2006). Heuristic-based information acquisition and decision making among pilots. *Human Factors*, 48, 734-746.
- Wilkinson, S. (1994). The November Oscar incident. *Smithsonian Air and Space*, February-March, 80-87.
- Woods, D. D. (1996). Decomposing automation: Apparent simplicity, real complexity. In R. Parasuraman, & M. Mouloua (Eds.), *Automation and human performance: Theory and applications* (pp. 3-18). New Jersey: Lawrence Erlbaum Associates.
- Woods, D. D., Dekker, S., Cook, R., Johannesen, L., & Sarter, N. B. (2010). *Behind human error*. Farnham, UK: Ashgate.
- Woods, D. D., & Sarter, N. B. (2000). Learning from automation surprises and "going sour" accidents. In N. B. Sarter & R. Amalberti (Eds.), *Cognitive engineering in the aviation domain*. Mahwah, NJ: Lawrence Erlbaum Associates. (pp. 327-353).
- Yates, J. F. & Stone, E. R. (1992). The risk construct. In J. F. Yates (Ed.), *Risk-taking behavior* (pp. 1-25). Chichester, UK: Wiley
- Yerkes, R. M., & Dodson, J. D. (1908). The relation of strength of stimulus to rapidity of habit-formation. *Journal of Comparative Neurological Psychology*, 181, 459-482.
- Zachay, D. & Wooler, S. (1984). Time pressure, training and decision effectiveness. *Ergonomics*, 27, 273-284.
- Zsombok, C. E., & Klein, G. A. (1997). *Naturalistic decision making*. Mahweh, NJ: Lawrence Erlbaum Associates.