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FINDING DECISIONS IN NATURAL ENVIRONMENTS:
TOWARD A THEORY OF SITUATED DECISION MAKING
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Finding Decisions in Natural Environments: Toward a Theory of Situated Decision Making

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Running Head: Finding Decisions....

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In keeping with the naturalistic decision making (NDM) tradition begun by Gary Klein, Jens Rasmussen, and others of studying "real people making real decisions" in their natural contexts, we sought to understand decision making by pilots in the often boring but frequently challenging world of flight. Our goal was to understand what constitutes effective flight crew decision making, as well as what conditions pose problems for crews and what leads to poor decision making.

As soon as we began looking carefully at decision strategies that distinguished more from less effective crews in simulated flight, we stumbled on an unexpected finding -- variability in the decision behaviors of the most effective crews. Sometimes the crews were very quick in making decisions, and sometimes they were very slow. In retrospect we shouldn't have been surprised to see this variability, but as psychologists we were looking for simple patterns, like good crews always making the fastest decisions.

These initial observations suggested that the most effective crews tailored their decision strategies to the features of the situation. Thus, our task became more complex. To understand what constituted an effective decision strategy we needed to understand something about the problem situations that crews encountered -- their underlying structures, demands, affordances, and constraints. Both our research questions and our methods shifted. The research question shifted from "What is the best decision strategy?" to "How can we assess the sensitivity and appropriateness of decision strategies in light of situational features?" Our method shifted from an exclusive focus on crew behavior to a dual focus on the situation and behavior.

Our approach builds on current efforts in the study of situated cognition (e.g., Hutchins & Klausen, 1991), and on Hammond's Cognitive Continuum Theory (Hammond, Hamm, Grassia, & Pearson, 1987). Hammond's view is that a good decision strategy matches the features of the situation. In the 70's he called for a theory of tasks, a plea that has largely gone unanswered. While we define situational features differently than he does, we agree with the intent of his statement. Our work also echoes the theme of Hart's work on "strategic behavior" (Hart, 1986). We are proposing the first tentative steps toward a theory of "situated decision making."

A SEARCH FOR DECISION EVENTS IN CONTEXT

As our starting point shifted from strategies to situations, we began a search for decision events in context. Our initial observations that revealed the variability in effective crew decision strategies was based on crews "flying" a mission in a high-fidelity flight simulator. From that data source we identified three distinct types of decision events. However, we realized that our opportunity to observe decisions was restricted by the particular scenario used in the study and so we sought a broader set of situations that might present other types of decision events.

Our solution was the Aviation Safety Reporting System (ASRS) data base. *Problem solving* and *decision making* were the key words we used to search the database (a second search was conducted using *emergency* as the keyword). These incident reports describe highly diverse events that require crew decision making. However, because of their self-report nature, they told us little about decision strategies or about conditions that may have led to poor decisions. We pursued yet another data source.

Accident investigations conducted by the NTSB offer deep analysis of actual cases, based on crew conversations documented by the cockpit voice recorder (CVR), physical evidence, aircraft systems, and interviews with survivors or observers. These case studies provide a fairly detailed picture of what happened immediately prior to the accident, what the crew focused on, how they managed the situation, what they did, and what decisions were made. The analyses are a good source of hypotheses about contextual factors that make decisions difficult and strategies that are effective for dealing with those situations.

What we have learned about decision situations and decision strategies from these three data sources will be described in the rest of this paper.

DECISION EVENTS

Simulator data

Our analyses were based on two full-mission simulator studies conducted at NASA-Ames Research Center . The first one by Foushee, Lauber, Baetge and Acomb (1986) was designed to study the effect of fatigue on crew performance, using 2-member crews. In a second study Chidester, Kanki, Foushee, Dickinson, & Bowles (1990) investigated leader personality effects, using 3-member crews. All crews were exposed to the same events, which allowed comparisons between crews in the way they responded to the scenarios. Crew performance was videotaped, transcribed and preserved for subsequent analyses.

Both studies confronted the participating pilots with similar problems: Crews were required to conduct a missed approach at their original destination due to bad weather, and they ultimately had to divert to an alternate landing site. During the climb-out following the missed approach, the main hydraulic system lost all fluid. As a result of this failure, the gear and the flaps had to be extended by alternate means. Moreover, the flaps could only be set to 15 degrees which implied a higher-than-normal landing speed, and gear could not be retracted once extended, meaning that further diversion was not desirable because of fuel constraints.

Three major decisions were present in these scenarios. (1) At the original destination, crews had to decide whether to continue with the final approach or to conduct a missed approach. (2) Once the crew realized that the weather at their destination was not improving, they had to select an alternate airport. (3) The hydraulic failure required crews to coordinate the flap and gear extension procedures during final approach at their ultimate destination, during an already high-workload period. These problems are characterized by differing levels of prescription of responses and by differing affordances. They also imposed different cognitive demands on the crews.

Problem (1) calls for a Go/No-Go decision. A highly proceduralized course of action is prescribed, assuming that all facilitating conditions are normal (the GO condition). If the go conditions are not met an alternate action is prescribed (the No-Go condition). Conditions for Go and No-Go are clearly defined and the actions to be taken in both cases are also clearly prescribed. The crucial aspect of the decision process lies with accurate situation assessment. The major impediment is ambiguity. These decisions are usually made under high time pressure and risk.

Selecting an alternate landing site as in problem (2) is an example of a choice problem. Several legitimate options or courses of action exist from which one must be selected. In those cases no simple rule prescribes the appropriate response. Options must be evaluated in light of goals and situational constraints, such as fuel, runway length, and weather.

Scheduling problems like problem (3) require that the crews decide on what is most important to do, when to do it and who will do it. Several tasks must be accomplished within a restricted window of time and with limited resources. Effective performance depends on good judgment about relative priorities and honest assessment of resources and limitations.

Aviation Safety Reporting System Reports

Ninety-four ASRS reports were analyzed in depth and classified in terms of their precipitating events, phase of flight during which the event and subsequent decisions occurred, and the focus of the decision. From these analysis three additional types of decisions were identified, as follows.

Condition-Action Rules. These decisions depend on If-Then rules. The situation requires recognition of the condition and retrieval of the associated response. These decisions are most similar to Klein's Recognition Primed Decisions (RPD), but are prescriptive in the domain. That is, they do not depend primarily on the pilot's past personal experience with similar cases, but on responses prescribed by the industry, company or FAA. Neither conditions nor options are bifurcated, as in Go/No Go cases, though both are types of rule-based decisions. Examples include decisions to shut down an engine when the engine oil is overheated or to descend to a lower altitude in case of rapid decompression. Basically the pilot must know the rule and then decide whether conditions warrant applying it.

Procedural Management. The essence of this class of decisions is the presence of an ambiguous situation combined with a judgment of high risk. The crew doesn't know what is wrong, but recognizes that something is out of normal bounds. Standard procedures are followed to make the situation safe, which may mean finding the nearest suitable landing site. These decisions look like condition-action rules, but without specifically-defined conditions, just general assessment of a high risk abnormal condition. Also the response is generalized, such as get down fast, or whatever seems appropriate to the condition. A case in the data base was the decision to reduce cruise speed when an airframe vibration was experienced (which turned out to be due to a loose trim tab). No specific rule guides this type of decision.

Creative problem solving. These are ill-defined and probably the least frequent types of decisions. No specific guidance is available in manuals, standard procedures or checklists to help the crew. The nature of the problem may or may not be clear, but even when it is clear no responses are prescribed. Candidate solutions must be invented. Perhaps the most famous case is the DC-10 (UA flight 232) that lost all flight controls when the hydraulic cables were severed following a catastrophic engine failure. The crew had to figure out how to control the plane. They invented the solution of using alternate thrust on the engines to "steer" it. An ASRS example shows similar ingenuity in a much less risky situation: The cockpit O2 bottles indicated below required levels on a long flight, fuel was limited, and the flight faced bad weather. The crew descended to FL250 and brought the flight-attendants' walk-around O2 masks into the cockpit, which would be legal in an emergency, even though they lacked microphones. This solution was preferable to a precautonary descent to an altitude not requiring oxygen because additional fuel would be burned at a low altitude, not desirable given the likelihood of holding or diverting due to bad weather.

NTSB Accident Analyses

A review of NTSB accident analyses reinforced the six types of decisions just described; no new types were discovered. The primary value of this data set is as a source of hypotheses about decision processes, about causes of poor decisions, and specification of antecedents to accidents. The NTSB seeks to understand causal and contributing factors in accidents. We selected for study only those cases in which crew actions were identified as contributing or causal factors.

DECISION STRATEGIES

Simulator data

Performance in simulators is the best source of process data, although it was limited in scope. Videotapes allowed us to observe decision making in action rather than relying on after-the fact accounts, as in the other data bases. How decision making evolves over time in response to dynamic situations can be analyzed. These data provide not only analysis of behavior but also analysis of crew communication as a window into the crew's thinking. Videotapes allow comparisons to be made between crews as they respond to the same event and within crews facing different decision events, thus yielding the greatest generality of findings.

Crew performance as they "flew" the simulator was evaluated both on- line and from videotapes by expert observers, in terms of operational and procedural errors. We identified higher and lower performing crews based on their error scores and then assessed their decision-relevant behaviors.

Highly effective crews demonstrated the following behaviors, which distinguished them from lower-performing crews:

- Appreciate the complexity of the decision situation and the significance of cues; are sensitive to constraints on the decision. Balance situational complexity and cognitive workload.
- Adapt their strategies to the situation, demonstrating a flexible repertoire.
- Monitor the environment closely and use more information in making decisions. If needed they manipulate the situation to obtain additional information in order to make a decision.
- Do not overestimate their own capabilities or the resources available to them.
- Plan for contingencies and try to keep their options open.

Less effective crews showed lower levels of all of the above behaviors.

ASRS

Little information on decision processes is available from ASRS reports due to the self-report nature of the data base. Pilots tend to report deviations from procedure, not decision processes. They tend to report WHAT they did, not HOW they did it. Pilots reported many events that we would classify as condition-action decisions, usually of a very routine nature. These tended to be safety-related procedures that followed immediately after failure of a system or recognition of a problem. After these initial "safing" actions, the harder decisions were made, such as whether or not to divert and where.

ASRS reports also revealed another point--the importance of diagnostic episodes in cockpit decision making. In many cases these were not minor efforts, but decisions in and of themselves, such as deciding that insufficient information is available to make a good decision and arranging conditions to get the needed information (e.g., fly by tower to allow inspection of landing gear; send crewmember to cabin to examine engine, aileron, etc.). Certain diagnostic actions served a dual purpose: the actions themselves could solve the problem as well as provide diagnostic information about the nature of the problem. The idea seemed to be, If this action fixes the problem, we will know what the problem was! This data set also helped to define those conditions that present ambiguous cues to decision makers.

NTSB

Accident investigations provide in-depth analyses of the conditions and behaviors associated with the accident. Since each analysis is a post-hoc case study, it does not permit definitive statements of the cognitive processes involved in the crew's interpretation of the situation and basis for decisions. However, they do provide a very rich descriptive base that permits some degree of aggregation across accidents. Also, analysts have an implicit model of what constitutes a good decision in the particular situation, which can be inferred from their evaluations of the crew's behavior and which, in turn, provides us with some insights into situational demands. We incorporated these insights into a simplified general decision model which we used as a template for characterizing crew behavior in subsequent analyses .

Our analysis of NTSB reports involving crew factors found that in most cases crews exhibited poor situation assessment rather than faulty decision making based on adequate situation assessment (Orasanu, Dismukes, & Fischer, 1993). This conclusion is based primarily on crew communication captured by the cockpit voice recorder (CVR). Crews that had accidents tended to interpret cues inappropriately, often underestimating the risk associated with a problem. A second major factor was that they overestimated their ability to handle difficult situations or were overoptimistic about the capability of their aircraft.

A recent analysis of flightcrew-involved accidents that occurred between 1978 and 1990 was recently completed by the NTSB (NTSB, 1994). Of the 37 accidents in which crew errors were identified as contributing factors, 25 (or about two thirds) involved what the authors called "tactical decision errors." These decision errors were second in frequency only to procedural errors, which occurred in 29 of the accidents.

Using our decision taxonomy as a frame to examine the tactical decision errors, we found that a large proportion of them (31/47) were Go/No-Go types of decisions, which should have been the simplest type of decisions. These included rejected take-offs, descent below decision height, go-arounds, and diversions. In all but one case, the crew decided to continue (Go) in the face of cues that suggested discontinuation (No Go) of the current plan. It should be pointed out that most Go/No Go decisions are made during the most critical phases of flight, namely take-off and landing, when time to make a decision is limited and the cost of an error is highest. Little room is available for maneuvering. In contrast, decisions made during cruise, even very difficult decisions, are not usually burdened with the double factors of time pressure and high risk. (Of course, there are a few notable exceptions like a cockpit fire or rapid decompression.)

CONCLUSIONS

Our examination of crew decision making from the perspective of three different data sources has led to the development of several tools and a set of converging observations about cockpit decision making. The three tools or concepts include the following:

- a taxonomy of types of decisions present in the aviation environment
- a model of factors that determine the amount of work that must be done to make a decision (a surrogate for decision difficulty, since we presently have no pilot-based difficulty data).
- a simplified decision process model appropriate to the aviation environment

Decision Event Taxonomy

Six types of decisions were identified (See Fig. 1 and Orasanu, 1993 for a fuller description). They fall into two sub-groups that differ primarily in whether or not a rule exists that defines a response appropriate to a given situation. The two rule-based decision types differ in whether binary options exist or whether a simple condition-action rule prevails. Non-rule-based decisions differ in how well-structured the problems are and in the kinds of options they offer. Thus the situations also differ in the cognitive work they require (outcome assessment, situation assessment, task prioritization, solution invention).

The terms Rule-Based and Knowledge-based are taken from Rasmussen (1983), but are used somewhat differently here because they define the kinds of decision situations, not the responses. Skill-based decisions were not included because of their automatic psychomotor nature.

Decision Effort Model

While we do not have experimental data on the cognitive complexity or difficulty of various decision events, we have a model that allows us to predict which decisions would involve the greatest amount of cognitive work. It involves factors that characterize the decision event. Two primary dimensions are situational ambiguity and response availability (see Figure 2). If a situation is ambiguous, more effort will be required to define the nature of the problem than if cues clearly specify the problem. Three types of ambiguity have been identified that may differ in their demands on the crew.

Vague cues. These cues are inherently ambiguous and nondiagnostic. They consist of vibrations, noises, smells, thumps and other nonengineered cues. Pilot knowledge and experience are critical to their interpretation. ASRS reports include cases of a ramp vehicle bumping into parked aircraft, a vibration during flight due to a loose aeleron-trim tab, and the sound of rushing air in the cockpit.

Conflicting cues. Cues of this type are clear and interpretable, often engineered diagnostic indicators. The ambiguity lies in the simultaneous presence of more than one cue that signal conflicting situations and opposing courses of action. For example, the presence of a stick shaker stall warning on take-off and engine indicators of sufficient power for climb are conflicting cues.

Uninterpretable cues. Again, these cues in themselves are clear, but in context are uninterpretable. As a result, the crew may disregard them or suspect that the indicator is faulty. A case of uninterpretable cues was the rapid loss of engine oil from both engines in synchrony during an overwater flight. The crew could not imagine a plausible scenario to explain these indicators, so ignored them and continued with their flight. Upon landing they discovered that caps had been left off both engine oil reservoirs after servicing. In fact, oil was being siphoned off during the flight and the indicators were accurately indicating this state of affairs.

At this point we do not have a sound basis for predicting the relative difficulty of these three types of ambiguity.

The second dimension determining problem complexity is response availability. The least work is required if a single response is prescribed to a particular set of cues (rule-based decisions). More work is required if multiple responses must be evaluated and either one must be chosen or multiple actions must be prioritized (see Payne, Bettman, & Johnson, 1993). The greatest effort will be required if no response options are available and one or more candidates must be created. Two other factors serve as multipliers of cognitive effort: time pressure and risk level. If time is short and risk is high, effort increases (Cf. Wright, 1974). These relations can be expressed by equation (1):

$$(1) \qquad PD = \frac{(SA \pm RA)\, r}{t}$$

where PD represents the Problem Demand level

SA represents Situation Ambiguity
RA represents Response Availability
r represents risk level
t represents time available

At this point the model is untested and serves mainly as a framework for understanding the relations among the various elements.

A Simplified Decision Process Model

The decision model we generated is a simple one (Fig. 3) and has many features in common with other decision models, especially Klein's RPD model (1989, 1993). We feel that its value lies in its simplicity. Two major components are involved: situation assessment and response selection. Situation assessment requires that the nature of the problem be defined and that risk level and time available to make the decision be assessed. Diagnostic actions may be taken to define the problem if the situation is not understood, providing time is available. External time pressures may be modified by crews to mitigate their effects (Orasanu & Strauch, 1994).

Selecting an appropriate response depends on the affordances of the situation. In some cases a single response is prescribed, in other cases multiple options exist from which one must be selected, in other cases multiple actions must all be accomplished within a limited time period, and in still other cases no response is available and one must be invented. In order to deal appropriately with the situation, the decision maker must be aware of what response options are available and what constitutes an appropriate process (retrieving and evaluating an option, choosing, scheduling, inventing). This process model serves as a frame for analyzing crew performance as described in NTSB accident reports and from tapes of full-mission simulation.

SUMMARY

A point we wish to emphasize is that different perspectives and insights into crew decision making were obtained from each of the data sources we examined. The full-mission simulator data and especially the ASRS reports provided insights into the types of decision events crews encounter. In contrast, the NTSB analyses are a valuable source of hypotheses about sources of decision difficulty and about where crews go wrong in decision making. The simulator data are especially useful for providing evidence on more and less effective decision strategies because of their controlled nature and the opportunity to observe multiple crews facing the same situations.

By using multiple sources of data we have been able to describe a wider set of decision events and associated decision strategies by flight crews than would have been possible by using only one source. These have given us a richer understanding of what constitutes effective decision making by flight crews. In general, effective strategies are appropriate to the situation, and more effective crews are more sensitive to those features, monitoring the situation to stay aware of present conditions and modifying their strategies as needed.

We have not yet evaluated what makes some decisions more difficult than others, but have created a model that makes predictions and that we plan to test. We recommend looking at the environment of interest very carefully and from many perspectives before drawing conclusions about what constitutes effective decision making in any non-laboratory environment of concern.

ACKNOWLEDGEMENTS

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References

Chidester, T. R., Kanki, B. G., Foushee, H. C., Dickinson, C. L., & Bowles, S. V. (1990). Personality factors in flight operations: Volume I. Leadership characteristics and crew performance in a full-mission air transport simulation. (NASA Tech. Mem. No. 102259). Moffett Field, CA: NASA-Ames Research Center.

Foushee, H. C., Lauber, J. K., Baetge, M. M., & Acomb, D. B. (1986). Crew factors in flight operations: III. The operational significance of exposure to short-haul air transport operations. (Tech. Mem. No. 88322). Moffett Field, CA: NASA-Ames Research Center.

Hammond, K. R., Hamm, R. M., Grassia, J., & Pearson, T. (1987). Direct comparison of the efficacy of intuitive and analytical cognition in expert judgement. IEEE Transactions on Systems, Man, and Cybernetics, SMC-17(5), 753-770.

Hutchins, E., & Klausen, T. (1991). Distributed cognition in an airline cockpit. Unpublished manuscript. University of California, San Diego, CA.

Klein, G. A. (1989). Recognition-primed decisions. In W. B. Rouse (Ed.), Advances in man-machine system research, 5, 47-92. Greenwich, CT: JAI Press.

Klein, G. A. (1993). A recognition-primed decision (RPD) model of rapid decision making. In G. Klein, J. Orasanu, R. Calderwood, & C. Zsambok (Eds.), Decision making in action: Models and methods. Norwood, NJ: Ablex.

National Transportation Safety Board. (1994). A Review of Flightcrew-Involved, Major Accidents of U.S. Air Carriers, 1978 through 1990. (PB94-917001, NTSB/SS-94/01). Washington, DC: Author.

Orasanu, J. (1993). Decision making in the cockpit. In E. L. Wiener, B. G. Kanki, & R. L. Helmreich (Eds.). Cockpit resource management (pp. 137-168). San Diego: Academic Press.

Orasanu, J., Dismukes, R. K., & Fischer, U. (1993). Decision errors in the cockpit. In Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting. Santa Monica, CA: Human Factors and Ergonomics Society.

Orasanu, J., & Strauch, B. (1994). Temporal factors in aviation decision making. In Proceedings of the Human Factors and Ergonomics Society Meeting. Santa Monica, CA: Human Factors and Ergonomics Society.

Payne, J. W., Bettman, J. R., & Johnson, E. J. (1993). The adaptive decision maker. New York: Cambridge University Press.

Rasmussen, J. (1983). Skill, rules, and knowledge: Signals, signs and symbols, and other distinctions in human performance models. IEEE Transactions on Systems, Man and Cybernetics. Vol. SMC-13, No. 3.

Wright, P. L. (1974). The harassed decision maker: Time pressures, distractions, and the use of evidence. Journal of Applied Psychology, 59, 555-561.

RULE-BASED DECISIONS ***(If x, then y)***

1. Go/No Go (Continue or cease planned action if condition *x* exists)
2. Condition Action (Recognize situation *y*, retrieve response *y*")

KNOWLEDGE-BASED DECISIONS

Well-Structured (problem situation is known; responses are available)

3. Choice (multiple response options available; choose one)
4. Scheduling (multiple response options available; schedule multiple)

Ill-Structured (problem situation not known; requires diagnosis; no response options readily available)

5. Procedural management (unable to diagnose situation; treat as if emergency and take necessary action)
6. Creative problem solving (diagnose situation, create solution)

Figure 1. A Taxonomy of Decision Types

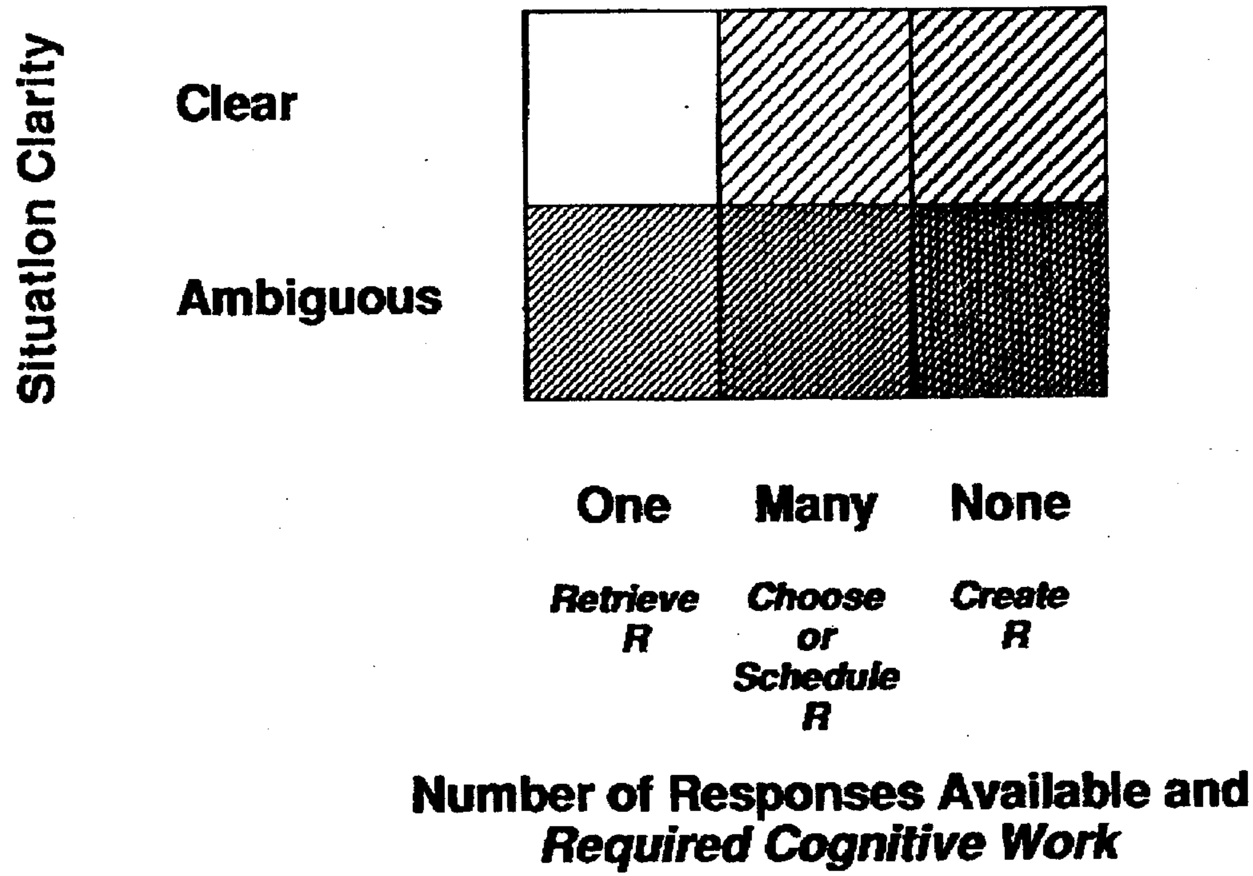

Figure 2. Decision Complexity as a Function of Situational Features (*Darker blocks are more complex*).

J. O[illegible], NASA

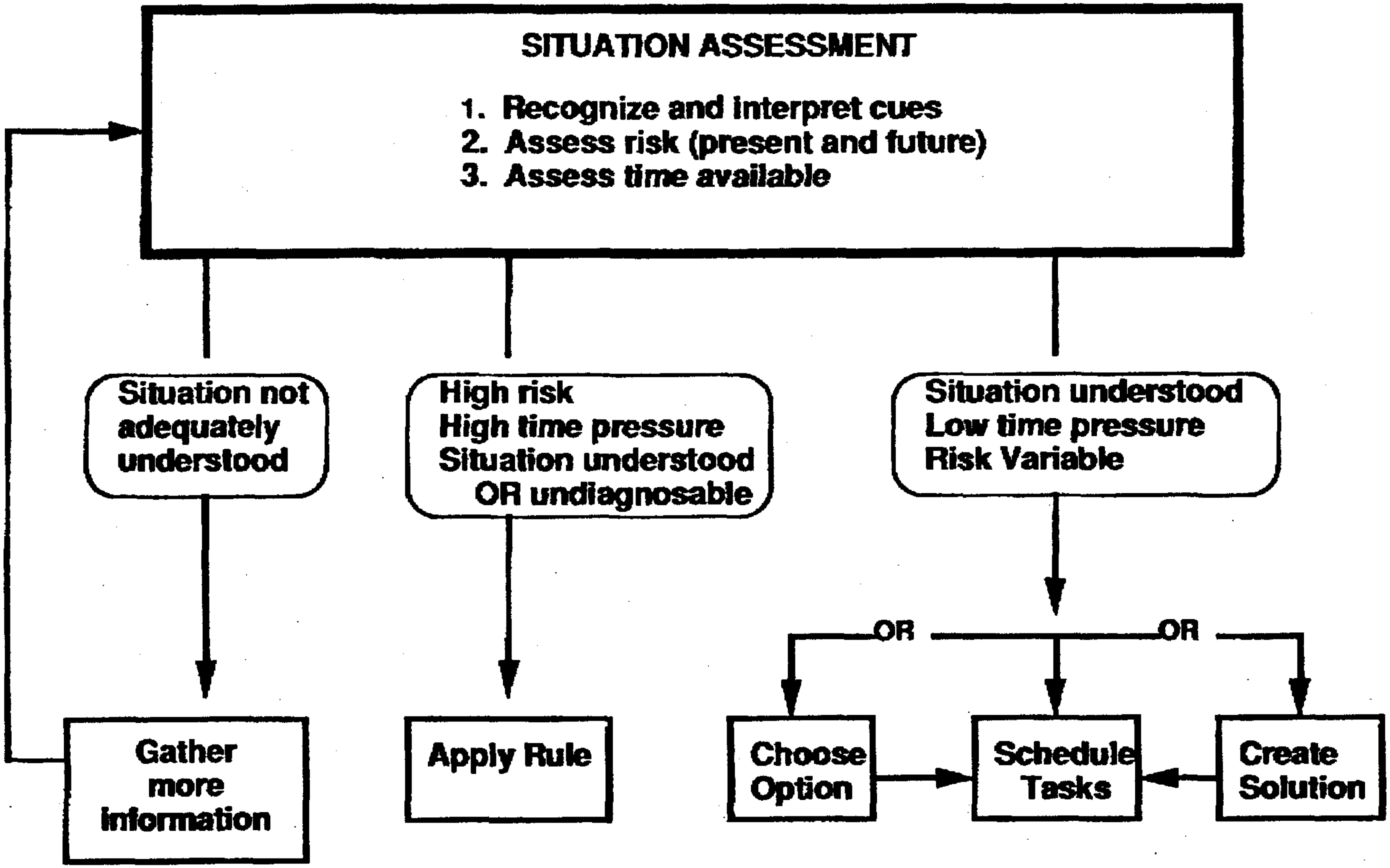

Figure 3. Simplified Decision Process Model

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