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Introduction to Cognitive Processes of Expert Pilots

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Final Report

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16. Abstract

This report addresses the historical problem that a very high percentage of accidents have been classified as involving "pilot error." Through extensive research since 1977, the Federal Aviation Administration determined that the predominant underlying cause of these types of accidents involved decisional problems or cognitive information processing. To attack these problems, Aeronautical Decision Making (ADM) training materials were developed and tested for ten years. Since the publication of the ADM training manuals in 1987, significant reductions in human performance error (HPE) accidents have been documented both in the U.S. and world wide. However, shortcomings have been observed in the use of these materials for recurrency training and in their relevance to more experienced pilots. The following discussion defines the differences between expert and novice decision makers from a cognitive information processing perspective, correlates the development of expert pilot cognitive processes with training and experience, and reviews accident scenarios which exemplify those processes. This introductory material is a necessary prerequisite to an understanding of how to formulate expert pilot decision making training innovations; and, to continue the record of improved safety through ADM training.

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PREFACE

The research effort reported herein was managed by the Federal Aviation Administration's System Technology Division (ARD-200) under contract to Advanced Aviation Concepts, Inc. (AAC). The initial need for the research grew out of the extensive, multiyear analysis of Aeronautical Decision Making (ADM) sponsored by the FAA which resulted in 10 published R&D reports. These reports included six (DOT/FAA/PM-86/41-46) on ADM for the spectrum of pilots from student/private to multi-crew resource management; and, four (DOT/FAA/DS-88/5-8) on Risk Management which treated pilot, operations manager and administrative aspects of reducing human error accident rates. The lessons learned from applying this training included the realization that basic differences existed between the cognitive processing of the novice or ab initio pilot and the more experienced pilot group, especially those pilot's who had been successful in making timely, accurate decisions under the extremely stressful conditions of accidents or incidents. The study methodology and research to explore and document these differences was proposed and conducted by Mr. Richard J. Adams of AAC.

In addition to the analysis of the cognitive processes of Expert Pilots, the material on expertise in various domains, the impact of time pressures, and the importance of practice provided the critical link between the observed cognitive behavior in aviation and the characteristics of expertise in other fields. Dr. K. Anders Ericcson of the Department of Psychology, the University of Colorado at Boulder provided this basic link and analysis.

ACKNOWLEDGEMENTS

The material presented in this report of exploratory research would not have been possible without the project direction and conceptual support of Dr. Ronald J. Lofaro of the FAA's Systems Technology Division. Dr. Lofaro's extensive background in crew resource management, non-linear decision making, and the modified Delphi paradigm for eliciting and evaluating expert opinions was crucial to the completion of the research in a timely and cost effective manner.

In addition, two individuals participated in the early development and formulation of this research. Dr. Robert Glaser of the Learning Research and Development Center, University of Pittsburgh was encouraging and helpful in identifying the basic traits of experts for review and analysis as they applied to aviation. Dr. Sallie E. Gordon of the Department of Psychology, University of Idaho provided guidance and knowledge in cognitive information processing and suggested developing research to modify current training programs to promote adaptive expertise in pilots.

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INTRODUCTION TO COGNITIVE PROCESSES OF EXPERT PILOTS

1.0 EXECUTIVE SUMMARY

Fifteen years of aviation research into the causes of human performance errors (HPE) in aviation provided a basis for the current study. Detailed analyses of human performance error accidents produced the conclusion that approximately half of these accidents were decision related. Since traditional pilot training stressed aeronautical knowledge and flying skills while relying on experience to teach and practice decision making, an obvious question was: Can we teach decision making as a way to accelerate the normal learning based on experience and to reduce these accidents?

1.1 Key Findings

- Aeronautical Decision Making (ADM) can be taught both in a classroom and a simulator environment. The principles and concepts of ADM have been accepted and used by a wide variety of civil and military aircraft users performing a multitude of missions.

- All formalized ADM training seems to improve safety through significant reductions in Human Performance Error accident rates.

- These widespread successes have generated a need for second generation ADM training materials for use in recurrency training and to more adequately address the cognitive processing needs of experienced pilots.

- The NTSB has recommended that the FAA pursue the implementation of ADM more vigorously following a fatal accident between an airplane and a helicopter in April 1991.

- Expert cognitive performance is characterized by rapid access to a well organized body of conceptual and procedural knowledge. This is a modifiable information structure based upon knowledge that is experienced. This experience allows the perception of large meaningful patterns in familiar and new situations which help the expert match goals to task demands. This means they can respond creatively or with opportunistic solutions based upon a global perception of the meaningful relationships in a situation.

• Experienced pilots have exhibited expert cognitive performance through keen, quick, confident decisions and almost a direct perception of the proper course of action. These decisions occur so rapidly it appears to be a cognitive process and behavioral resultant based upon insight or intuition. This intuitive performance is based upon: experience (cognitive and sensory, internal and external); the cues and context of the situation; and, the expert's ability to identify causal relationships in a situation.

• The development of these expert pilot cognitive processes can be correlated with the growth in other aviator skills which result from training and experience. The ability to develop a second generation of ADM materials to teach or train these skills will require a more thorough understanding of how experts use past experience to assess new situations, make decisions and define goals.

• The expert pilot is adaptive. He/she can perceive the necessity to alter (or not to alter) ingrained conceptual and procedural knowledge based upon the parameters and dynamics (cues and context) of the problem or situation encountered.

• Experiencing situations repeatedly throughout an aviation career enhances a pilot's cognitive processing by providing reinforcement of knowledge to apply to similar new situations, by providing more associative paths to speed-up recall of knowledge and by providing elaborations on previous situations which can be used for both recall and inference.

• Experience can also interfere with the perception of a situation and provide negative reinforcement for later use in bad decision making. Job or personal stress, anxiety, fixation, emotional blocking, etc. will affect the stored knowledge negatively and it will not be usable in new situations.

• Experience or training that is intended to be used for the development of expert pilot cognitive processing development must insure the perception of the essential psychophysiological elements of the problem. The appropriateness of the experience will be critical to the subjective associations and stored knowledge patterns that will be used in new situations.

1.2 History and Successes

Extensive research and empirical testing in Aeronautical Decision Making (ADM) produced a series of fifteen Federal Aviation Administration manuals and reports on ADM (1986-1988) as shown in Table 1.

Table 1 **SUMMARY OF ADM TRAINING MATERIALS**

REPORT NUMBER	TITLE
FAA/PM-86/41	ADM for Student and Private Pilots
FAA/PM-86/42	ADM for Commercial Pilots
FAA/PM-86/43	ADM for Instrument Pilots
FAA/PM-86/44	ADM Instructor Guide for Student and Private Pilots
FAA/PM-86/45	ADM for Helicopter Pilots
FAA/PM-86/46	ADM - Cockpit Resource Management
FAA/DS-88-5	Air Amb Heli Pilots- Learning from Past Mistakes
FAA/DS-88-6	Air Amb Heli Pilots- Situational Awareness Exercises
FAA/DS-88-7	Risk Management for Air Ambulance Heli Operators
FAA/DS-88-8	ADM for Air Ambulance Hospital Administrators
AC 60-22	ADM Advisory Circular
unassigned	Air Traffic Controller Decision Making Training Mtls
unassigned	ADM Techniques for the Practical Test Guide
unassigned	Back to Basics Introduction to ADM
TE01P12	ADM for Natural Resource Pilots

These ADM training manuals covered the range of pilots from student/private candidates to multi-crew resource management, as well as, reports devoted to helicopter pilots, EMS pilots, and Natural Resource pilots. In addition, ADM reports were developed for EMS operator risk management, hospital administrator ADM and Air Traffic Controller decision making.

It is difficult to accurately assess the general impact of all of the manuals throughout aviation since the manuals are available upon request and not ordinarily used in a formal course or set of courses. However, several specific areas have shown dramatic effects. Bell Helicopter Textron attributes the following very significant reductions in all Human Performance Error (HPE) accidents to the introduction of the ADM materials in their annual Jet Ranger (B206) safety seminars:

- A **36.2%** reduction *worldwide* during the period 1987-1990 (9.3 million hours were flown in this period).

- A **48.2%** reduction in the *U. S.* comparing before ADM (1984-86) to after ADM (1987-88).

- A **72.3%** reduction in the *U. S.* pre and post ADM for accidents involving weather decisions.

The dramatic (48-72%) *U. S.* reductions are particularly significant when one realizes that the Bell Jet Ranger is the helicopter that flies **45.6% of the flight hours** of the entire fleet of U. S. helicopters (0.9 to 1.1 million hours annually). This fact resulted in this conclusion of a recent Bell report (Fox 1991):

> **"The recent concentrated Judgment Training/ADM/PDM efforts of manufacturers, operators and regulatory agencies have made a significant reduction in human error accidents. Major improvements in helicopter safety for the future requires the continuation and refinement of these safety efforts."**

The Bell results substantiate the results of the six FAA ADM evaluation studies performed prior to publication of the training manuals. These empirical tests showed the effectiveness of the training varied (Diehl 1989) from 8% in a voluntary, minimally structured, manual reading situation to 46% for a well structured, comprehensive ground school environment with simulator training. (Note: All six tests were statistically significant at or beyond the .05 level of confidence.)

Table 2 provides data on the worldwide civil and military safety improvements along with the earlier FAA experimental results. The military data were published in a paper (Diehl 1991) entitled "The Effectiveness of Training Programs for Preventing Aircrew 'Error' ". As shown in the table, the Air Force and Navy data (Alkov 1991) further substantiate the validity and worth of the FAA research and ADM training.

Table 2 **ADM SUCCESSES**

DATA SOURCES	HPE REDUCTIONS
10 EXPERIMENTAL VALIDATIONS	8 - 46%
WORLDWIDE CIVIL HELICOPTERS (BELL 206)	
√ ALL HPE ACCIDENTS	36%
√ WEATHER RELATED ACCIDENTS	72%
U. S. CIVIL HELICOPTERS	
√ B206 ALL HPE ACCIDENTS	48%
√ LARGEST CIVIL OPERATOR	54%
U. S. MILITARY	
√ USAF MAC TRANSPORT CREWS	51%
√ USN HELICOPTERS	28%
√ USN AIRPLANES (A6 & EA6)	81%

1.3 Lessons Learned

The bottom line can be stated as follows:

> **In all instances, Aeronautical Decision Making training has had a significant impact on improving safety through significant reductions in human error accident rates.**

In addition to these documented safety improvements, we have learned that decision making or judgment can be taught in a classroom or simulator environment. ADM has also been accepted by a wide variety of aircraft users or operators performing a multitude of missions as previously shown in Table 2.

These widespread successes generated a request from the civil helicopter operators for additional ADM material for use in recurrency training. They also led the National Transportation Safety Board to recommend that the FAA pursue the implementation of ADM more vigorously (NTSB 1991) following a fatal accident involving an airplane and a helicopter. However, as clear-cut as these improvements have been, a more detailed examination of the accident rate reduction data disclosed the major impact has been on the less experienced pilots (6 months to 5 years). This finding led to the industry questions: Can we achieve the same impact in human error reduction of the more experienced pilots? And, how can this be done?

The current research effort is an attempt to respond to these industry requests. It is also based upon parallel events occurring in the air carrier industry during the 1983-1989 timeframe. During this period, there were several extraordinary accidents involving multiple engine failures, explosive decompressions caused by structural failures, fuel starvation and in-flight fires. In each of these accidents, experienced pilots quickly responded to emergencies for which there were no handbook procedures or previous training. They assessed the situation and <u>integrated</u> airmanship skills, trained procedures and aeronautical knowledge into a quick, effective decision making process. Such dynamic cognitive behavior was in direct contrast to the more basic ADM training which stressed a linear, measured approach to situation analysis.

We appear to have come full circle. The earlier research demonstrated that decision making could be taught in lieu of total reliance on the "school of experience". However, this training was successful only in terms of reducing accidents of the less experienced pilots. The observations of the more dynamic, complex decision making of the experienced pilots during extraordinary "saves" illustrated the need for further understanding of expert cognitive processes.

This report provides an introduction to the differences between expert and novice decision making processes as they apply to aviation situations and training. The objectives of this presentation are to raise the awareness of these differences and to

provide the foundation of common knowledge necessary to develop future training programs to maximize expert cognitive processing in pilots. This introductory material is necessary to an understanding of how to formulate Expert Decision Making materials for use in second generation training; and, to continue the record of improved safety through ADM materials and training.

2.0 INTRODUCTION

Judgment and decision making are essential piloting skills and critical to safe flight. In general, decision making requires two types of judgment: *evaluation* and *prediction*. Although decisions must be founded in aeronautical knowledge, trained procedures, flying skills and experience, it is often difficult to isolate and describe the decision making role or the order in which this knowledge is used in actual flying situations. **In fact, the degree to which the conscious use of these structured abilities are employed varies considerably from the novice to the highly experienced pilot.**

For example, airline pilots have observed that in the beginning of their experience, they had to consciously work at being "on-top" of flying the airplane, whereas, later in their careers they simply "experienced" the act of flying. The same transition has been appreciated by all pilots from small fixed wing student/private pilots to helicopter and fighter pilots. Sometimes the transition from thinking about flying to merely doing it has occurred more than once during their evolving flying careers. Yet, the mechanism behind this transition is not clearly understood and typically it has been assumed that learning to make good decisions could only be achieved through experience. However, the school of experience is the toughest in existence since it always "gives the test before you complete the course".

Research to date in Aeronautical Decision Making (ADM) has demonstrated that pilot judgment behavior is learned and, therefore, can be shaped through training. Fifteen years of research including six validation tests (Diehl and Buch, 1986) in the U.S. and Canada have documented that a structured approach to ADM training can enhance a pilot's application of conventional flight training, knowledge, skill, and experience. In addition, the civil and military helicopter and airplane operator successes with ADM have validated this research. However, as successful as it has been, the current approach to teaching pilot decision making has two limitations. First, it is constrained by a *deductive* approach to the decision process based upon a linear model described by the acronym "DECIDE". Second, it is limited in scope to an introductory level course in how to make good decisions which leaves instructors and operators with the frustration of what to do next. Figure 1 presents the major elements of this model.

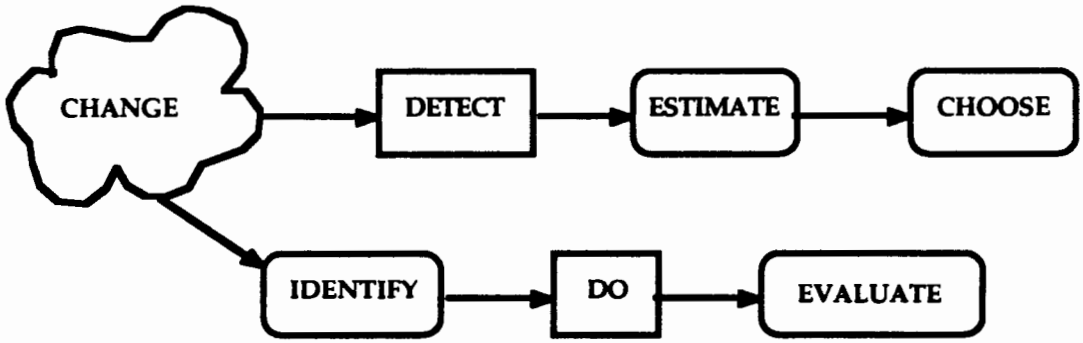

Figure 1 **THE DECIDE MODEL FOR AVIATION DECISION MAKING**

Regarding the deductive reasoning constraint, the DECIDE model has two deficiencies. First, it is too long and difficult to remember (Detect, Estimate, Choose, Identify, Do, and Evaluate). Second, it advocates sequential consideration of alternative decisions and possible outcomes to respond to a changing situation (sometimes a rapidly deteriorating one). This decision process is informative and useful to the neophyte pilot in a learning mode, but it does not represent how experienced pilots make decisions especially in emergency situations. For example when fuel burn rate is noted to be faster than planned, an inexperienced pilot may: recalculate fuel reserves to his destination or an alternate, look at options for an additional enroute fuel stop, replan the rest of the flight, etc. In contrast, the experienced pilot may quickly decide an interim stop is necessary, regardless of the impact on his flight plan, based solely upon previous similar circumstances with the same aircraft, passenger load and geographic location.

In fact, there are additional problems with linear analytical models like DECIDE. First, they fail to take into account important strengths of experienced decision makers. Second, it is very often impractical to carry out the linear analyses under conditions of time pressure. Finally, the methods are difficult to apply to problems with ambiguous or incomplete information. In the real world, there are documented differences between novice and expert decision makers (Ortega, 1989; Chi and Glaser, 1981; Reitmann, 1980; and Kahneman, 1972) which will be explored in the aviation environment.

2.1 Pilot Decision Making Training

Recent research has shown that, within their domain of expertise, experts have acquired methods for superior perception, memory and integration of information. In pilots, these skills provide keen, quick, confident decisions almost as if the proper course of action is a perceived characteristic of the current situation. The experienced pilot maintains an accurate detailed description of the current situation allowing them to continuously monitor incoming new information in terms of its

relevance to continued safe flight. As part of this "perceptual" process, the experienced pilot notices important relations and meaningful patterns of information (chunks), which leads to the automatic retrieval of relevant courses of action from memory. In the experienced pilot, the deliberate search for specific information as well as the careful execution of sequences of steps in a procedure used by the novice has been transformed into a continuous updating of the current situation with direct retrieval of the appropriate course of action. Structured, sequential decision procedures have been transformed into direct retrieval of the correct decision for that particular situation.

These facts lead to an interesting contradiction. Prior to the development of ADM training it was widely held that good judgment could only be learned through experience. The 15 years of ADM work has amended this view to include the fact that ADM can be taught effectively in a classroom or simulator environment. However, we have now realized that there is another, more subtle use of experience on decision making in which decisions are directly retrieved from memory without any traces of intermediate steps in the experts' awareness. Aviation decision making, especially in a novel situation (i.e. emergency) characterized by rapid, unexpected changes and crises, requires an adept use of both deductive and inductive reasoning powers

This leads to a need for analyzing research on expert versus novice decision making and its implications for aviation; the exploration of the role of inductive reasoning in the decision making process; and, the characterization of *expert* pilot decision making skills.

The following discussion recognizes that most real decisions are based on an often unstructured use of available knowledge, skills and the situation. A major goal of this effort is to help pilots make better decisions and, in particular, to expedite the transition from novice to expert pilot by providing an understanding of the cognitive processes needed and developing an expert level training structure for the process.

2.2 Aviation Decision Making Requirements

Decision making and judgment are pervasive throughout a pilot's career and an integral, important part of each flight. From the initial go/no-go flight planning decision to the final approach direction at the heliport or the landing pattern to use at an uncontrolled airport and including where to safely park, two kinds of decisions are common. First, pilots make value assessments by which they express preferences: for example, which aircraft to rent or use, which route offers the best NAVAIDs, safest altitudes to use, etc. Second, pilots make predictions that reflect what they expect to happen: for example, estimating time of departure, selecting the optimum weather route, calculating fuel reserve requirements, etc. In short, decision making is an inevitable aspect of flying.

Despite the inevitability of pilot decision making, it is a curious fact that pilot training at all levels consists of detailed study of aeronautics, aircraft systems, aircraft performance, meteorology, emergency procedures, navigation, air traffic control procedures, airspace restrictions, etc., however almost no time is spent on instruction concerning conceptual skills and, in particular, the cognitive processes needed to sort, organize and apply this substantive knowledge.

Experienced pilots develop the ability to perceive and place data into large, meaningful patterns, this ability includes the actual perception of the pattern itself. This pattern recognition occurs so rapidly it appears to be a keen, quick *insight* and almost a direct perception of the proper course of action. This cognitive functioning of experts is manifested in many fields and appears to be a cognitive process and behavioral resultant based upon *intuition* . However, related research has shown that this ability of experts appears to depend on the nature and organization of the knowledge in existing memory. **For this analysis, intuition is equated to the exercise of mature and practiced understanding, an effortless and often experiential (rather than deliberative/consciously striving) process.**

Intuition is then a type of skill acquisition -- the (intuitive) ability to use patterns without decomposition, or a "know-how" which is the product of deep situational awareness/involvement. As stated in a recent AOPA Pilot article (Collins 1989) "An intuitive pilot is less likely to be surprised, and avoiding surprises is a key to flying well".

The skilled, intuitive private pilot "knows when" the weather is about to defy the forecast. He has the ability to quickly become aware of a problem or change and the insight necessary to respond in a timely manner. On the ground, he is the pilot who occasionally scrubs a flight because he does not feel right about the weather, the airplane or himself. Inflight, the intuitive pilot monitors, anticipates and considers the need for action in advance of the moment it is required. For example, he might configure the aircraft for rough running based upon the anticipation of turbulence when moving into an area of weather.

2.3 Expert Pilot Decisions

Six air carrier accidents illustrate how experienced pilots make decisions in "untrainable " emergency situations.[1] Table 3 provides typical examples. The United Airlines DC-10 engine explosion and landing at Sioux City, Iowa; the cargo door failure that left a gaping hole in United Airlines flight 811 (a B-747) during climb-out, the Aloha Airlines B737 fuselage failure; and, the Air Canada B-767 fuel starvation accident were all situations for which there were no specified procedures, no previous simulator training and certainly no past experience. The following paragraphs review each of these accidents to provide the empirical basis for the role of expert cognitive processes in pilot decision making. Each accident is presented as an accident summary, event history, decision process analysis and conclusions.

Table 3 **EXPERTISE IN AVIATION EMERGENCIES**

DATE	LOCATION	AIRLINE	AIRCRAFT	REPORT NO.	ACCIDENT TYPE
7-19-89	SIOUX CITY, IA	UAL	DC-10-10	NTSB/AAR-90/06	ENGINE FAILURE
2-24-89	HONOLULU, HI	UAL	B-747-122	NTSB/AAR-90/01	CARGO DOOR FAILED
4-28-88	MAUI, HI	ALOHA	B-737-200	NTSB/AAR-89/03	STRUCTURAL FAILURE
7-23-83	GIMLI, CAN.	AIR CANADA	B-767	CANADA	FUEL STARVATION
6-02-83	CINCINNATI	AIR CANADA	DC-9-32	NTSB/AAR-86/02	ON-BOARD FIRE
6-12-72	WINDSOR, CAN.	AAL	DC-10-10	NTSB/AAR-73/02	CARGO DOOR FAILED

2.3.1 DC-10 Catastrophic Engine Failure & Loss of Hydraulic Systems

SUMMARY -- On July 19, 1989, at about 3:00 pm local time, a DC-10 operated by United Airlines as flight 232, experienced a catastrophic failure of the No. 2 tail mounted engine during cruise flight. Shortly after the engine failure, the crew noted that the hydraulic fluid pressure and quantity had fallen to zero in all three redundant hydraulic systems. The engine failure precipitated damage that severed the three hydraulic systems, leaving the flight control systems inoperative. Approximately one minute after the engine failure, the flight data recorder indicated no further movement of the flight control surfaces.

The only means of control for the flight crew was from the operating wing mounted engines. The application of asymmetric power to these engines changed the roll attitude, hence the heading. Increasing and decreasing power had a limited effect on the pitch attitude. The airplane tended to oscillate about the center of gravity in the pitch axis. It was not possible to control the pitch oscillations with any degree of

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[1] "Untrainable" in this context refers to the inability to train all possible combinations of all possible errors, malfunctions, weather, etc. It also includes the fact that within all reasonable statistical criteria, the aircraft manufacturers, the airline, the regulatory agencies, the insurance companies, etc. can not conceive of unique, never before experienced failures such as explosive decompression caused by separation of a large segment of aircraft fuselage.

precision. Moreover, because airspeed is primarily determined by pitch trim configuration and power, there was no direct control of airspeed. The crew found that despite their best efforts, the airplane would not maintain a stabilized flight condition. The airplane subsequently crashed during an attempted landing at Sioux Gateway Airport, Iowa. There were 285 passengers and 11 crewmembers onboard. One flight attendant and 110 passengers were fatally injured.

EVENT HISTORY -- About 1 hour and 7 minutes after takeoff, the flight crew heard a loud bang or an explosion, followed by a shuddering of the airframe. The following sequence of events is in chronological order and is presented to summarize the type and variety of circumstances comprising the decision making environment.

1. The flight crew determined that the No. 2 aft (tail mounted) engine had failed. The captain called for the engine shutdown checklist. While shutting down the engine, the second officer (flight engineer) observed that the systems hydraulic pressure and quantity gauges indicated zero.

2. The first officer advised that he could not control the airplane as it entered a right descending turn. The captain took control of the airplane and confirmed that it did not respond to flight control inputs.

3. The captain reduced thrust to the No. 1 engine and the airplane began to roll to a wings level attitude.

4. A flight attendant advised the captain that a UAL DC-10 training check airman was seated in the passenger compartment and had volunteered his assistance. The captain immediately invited the airman into the cockpit.

5. At the request of the captain, the check airman re-entered the passenger cabin and performed a visual inspection of the airplane's wings. He returned and reported that the inboard ailerons were slightly up, not damaged, and that the spoilers were locked down. There was no movement of the primary flight control surfaces.

6. The captain directed the check airman to operate the throttles to free himself and the first officer to attempt to maintain command of the flight controls. The check airman advised that the No. 1 and No. 3 engine thrust levers could not be used symmetrically, so he used two hands to manipulate the throttles. Even so, he said that the airplane had a continuous tendency to turn right and it was difficult to maintain a stable pitch attitude.

7. The captain reported to the approach controller that: the flight had no elevator control, they might have to make a forced landing and asked the controller for the ILS frequency, heading to the runway and length of the runway. He then instructed the second officer to start dumping fuel using the quick dump.

8. The captain asked the senior flight attendant if everyone in the cabin was ready. She reported in the affirmative and that she observed damage on one wing. The captain sent the second officer back to inspect the empennage visually.

9. The second officer returned and reported damage to the right and left horizontal stabilizers. The captain replied "that's what I thought". The captain then directed the flightcrew to lock their shoulder harnesses and to put everything away.

10. Several seconds later, the controller alerted the crewmembers to a 3,400 foot tower obstruction located 5 miles to their right and asked how steep a right turn they could make. The captain responded that they were trying to make a 30 degree bank. A crewmember commented that "I can't handle that steep of bank". The first officer stated, "we're gonna have to try it straight ahead Al..."

11. The captain reported the runway in sight and thanked the controller for his help. The controller stated that the runway the flight had lined up with was closed, but he added "that'll work sir, we're gettin' the equipment off the runway". The captain asked its length and the controller reported 6,600 feet. Twelve seconds later the controller stated that there was an open field at the end of the runway and that the winds would not be a problem.

12. During the final 20 seconds before touchdown, the airspeed averaged 215 knots, sink rate was 1,620 feet per minute and smooth oscillations in pitch and roll continued. The captain recalled getting a high sink rate alarm from the ground proximity warning system and that at 100 feet above the ground, the nose of the airplane began to pitch downward. First contact was made by the right wing tip followed by the right main landing gear. The airplane skidded to the right of the runway, ignited, cartwheeled and came to rest in an inverted position.

DECISION PROCESS ANALYSIS -- Although transcripts of the Cockpit Voice Recorder (CVR) are not available in the published NTSB accident report, Captain Al Haynes reported in a speech on January 26, 1991 that the transition from a normal, "uneventful" takeoff and climb to 37,000 feet to a nearly "uncontrollable" aircraft occurred in about 15 seconds. Although the copilot was flying this portion, when the failure occurred, the captain took control of the aircraft and quickly verified that full left aileron and full back elevator could not stop the descending right hand turn. In fact, with both pilots on the controls, the descending 38 degree right bank could not be arrested. This situation is an excellent example of the variety of tasks and extreme decision making environment faced by a pilot during emergency situations.

The events which comprise this accident aptly illustrate the dire need for reliance on the pilot's cognitive powers of perception, procedural knowledge, evaluative and predictive judgment. They also illustrate the immediate response of an experienced pilot in reverting to basic airmanship skills (i.e., figuring out how to fly the airplane) and the importance of ingrained training in crew resource management. The captain's "immediate" decision to use the abilities of the check airman, his concern

and coordination with the flight attendant, his utilization of the second officer for damage assessment, and his professional communication with the air traffic controller all document an experienced pilot's ability to formulate and carryout a reasonable, team approach to the problem or situation while maintaining mental composure under extreme time pressures.

Finally, the results of these controlled decisions are evidence of the pilot's ability to adapt to a difficult situation, organize his thoughts, use trained skills, establish subgoals and goals to match the demands of the problem. Specifically, his use of the check airman and flight engineer illustrate the implementation of Crew Resource Management training. However, even with full utilization of the available personnel, pitch oscillations and roll reversals from 4-28 degrees of bank were as stable an approach as the aircraft could make. Regardless, Captain Haynes reported that he was always "confident of getting the aircraft on the ground".

CONCLUSIONS -- Simulator reenactment of the events leading to the crash landing revealed that the line flight crews could not be taught to control the airplane and land safely without hydraulic power available to operate the flight controls. In general the reenactments indicated that landing parameters, such as speed, touchdown point, direction, attitude, or vertical velocity could be controlled separately, but it was virtually impossible to control all parameters simultaneously. The NTSB stated that under the circumstances the UAL flightcrew performance was highly commendable and greatly exceeded reasonable expectations.

2.3.2 B-747 Explosive Decompression

SUMMARY -- On February 24, 1989, United Airlines flight 811, a Boeing 747 was being operated as a regularly scheduled flight from Los Angeles, California to Sydney Australia with intermediate stops in Honolulu, Hawaii and Auckland, New Zealand. There were three flightcrew, 15 flight attendants and 337 passengers aboard the airplane.

The flight crew stated that the first indication of a problem occurred while the airplane was climbing between 22,000 and 23,000 feet at an indicated airspeed of 300 knots. They heard a sound, described as a "thump", which shook the airplane. They said that this sound was followed immediately by a "tremendous explosion". The airplane had experienced an explosive decompression. They said that they donned their respective oxygen masks but found no oxygen available. Engines No. 3 and 4 were damaged from foreign object ingestion and had to be shutdown.

EVENT HISTORY -- Less than 20 minutes out of Honolulu, flight 811 experienced something that statistically never should have happened, the simultaneous loss of power from two of the B-747s four engines on the same side of the aircraft. The following events summarize this unexpected decision making situation.

1. Cargo door blew open leaving a 10' x 15' hole in the right side of the fuselage.

2. The cargo door separation resulted in the loss of: the fuselage shell structure above the cargo door; the main cabin floor structure below seats 8GH through 12GH; and, nine passengers.

3. The captain immediately initiated a controlled descent, turned 180 degrees to the left to avoid a thunderstorm, and proceeded to Honolulu.

4. The first officer squawked 7700 and declared an emergency to the enroute center air traffic controller.

5. The No. 3 engine was shutdown due to heavy vibration, zero compressor speed indication, low EGT and low EPR.

6. The second officer was sent to inspect the cabin area and returned to inform the captain that a portion of the forward right side of the cabin fuselage was missing.

7. The captain noticed flashes of fire in the No. 4 engine along with low compressor speed and high EGT. He elected to shutdown the engine.

8. The flightcrew initiated fuel dumping during descent to reduce landing weight.

9. The airplane was cleared for an approach to Honolulu runway 8L.

10. The final approach was flown at 190-200 knots with only No. 1 and 2 engines.

11. During flap extension, the flightcrew observed an indication of asymmetrical flaps as the flap position approached 15 degrees.

12. The airplane touched down on the runway approximately 1000 feet from the approach end and stopped about 7000 feet later with idle thrust reversers on the operating engines and moderate to heavy braking.

DECISION PROCESS ANALYSIS -- The pilot of United Airlines' flight 811 used expert cognitive skills in handling the multiple emergencies that resulted from the large hole left in the fuselage when the cargo door blew off. He was faced with the failure of two engines on the same wing and a malfunctioning emergency oxygen system as he reached 22,000 feet.

The trained procedure for a sudden aircraft depressurization is to execute a power dive. But, in a critical decision, he opted to be cautious and descend at a much slower speed. He slowed the B747 to as close to stall speed as possible in order to keep the air rushing over the plane from further widening the hole or doing more damage to the wing. The trick was not to go too slow. Since the hole changed the aerodynamics of the plane, he really did not know the stall speed under these circumstances and had to rely on basic airmanship skills to make this crucial

judgment. **This decision is exemplar of an experienced pilot's ability to rapidly access his well organized knowledge base and his ability to modify its application to the unique demands of the situation.**

Upon reaching 4000 feet safely, the captain was faced with insufficient time to dump the remaining 300,000 pounds of fuel; and, flaps that could only be extended 10 degrees rather than the normal 20 degrees for a two engine landing. He quickly and confidently decided to land as soon as possible. This meant landing at 195 miles per hour vs the normal 170 mph and landing about 36,000 pounds over Boeing's recommended maximum stress load of 564,000 pounds. **This series of decisions demonstrate his ability to form a mental representation of a situation with multiple possible interpretations and to build a "plan" in a rapid, near instantaneous manner.**

With fire trucks and ambulances standing by, the Captain made what some flight attendants later told investigators was one of the smoothest landings they had experienced (Valonte, 1989). In this case, the pilot's skill and expertise provided an improvisation (creative solution) to keep the plane from crashing. This example further illustrates that expert decision making is not only fast, but also accurate.

CONCLUSIONS -- The airplane made a successful emergency landing at Honolulu and the flightcrew successfully evacuated 328 passengers. Examination of the airplane revealed that the separation of the forward lower cargo door had caused extensive damage to the fuselage and the cabin structure adjacent to the door. Nine of the passengers had been ejected from the airplane and lost at sea.

United Airline's Vice President for standards and training stated: "There are procedures to follow for every problem he (the pilot, ed.) ran into. But pilots aren't ordinarily trained to handle two or three emergencies all happening at the same time. That the crew on Flight 811 did this is really the miraculous part".

2.3.3 <u>B-737 Fuselage Separation</u>

SUMMARY -- On April 28, 1988 a Boeing 737-200 operated by Aloha Airlines Inc. as flight 243 experienced a structural failure, fuselage separation and explosive decompression. The flight was enroute from Hilo to Honolulu, Hawaii at 24,000 feet when the failure occurred. Approximately 18 feet of the cabin skin and structure aft of the cabin entrance door and above the passenger floor line separated from the airplane during flight. There were 89 passengers and 6 crewmembers on board. One flight attendant was pulled out of the main cabin during the decompression and is presumed to have been fatally injured. Seven passengers and 1 flight attendant received serious injuries. The crew performed an emergency descent and landing at Kahului Airport on the island of Maui.

As the airplane leveled at 24,000 feet, both pilots heard a loud "clap" or "whooshing" sound followed by a wind noise behind them. The first officer's head

was jerked backward, and she stated that there was debris, including pieces of gray insulation, floating in the cockpit. The captain observed that the cockpit entry door was missing and that "there was blue sky where the first-class ceiling had been". He described the airplane attitude as rolling slightly left and right and that the flight controls felt "loose".

EVENT HISTORY -- After the fuselage separation, the flight crew found themselves in a "novel" aviation situation which had never been experienced in either actual flight or any training situation. The following event chronology documents the type and variety of decision related cognitive tasks.

1. Although the first officer conducted the takeoff and climb to enroute altitude, the captain immediately took over the controls of the airplane. Because of the decompression, both pilots and the air traffic controller in the observer seat donned their oxygen masks. The captain also actuated the passenger oxygen switch.

2. The captain began an emergency descent. He extended the speed brakes and descended at an indicated airspeed of 280-290 knots. The first officer stated that she observed the rate of descent at 4100 feet per minute at some point during the emergency descent.

3. Because of the ambient noise, the pilots initially used hand signals to communicate. In addition, the first officer said she could not hear any radio transmissions from the Honolulu Air Traffic Control Center after tuning the transponder to emergency code 7700 and notifying them that the flight was diverting to Maui.

4. When the airplane descended through 14,000 feet, the first officer switched the radio to Maui Tower frequency, informed them of the rapid decompression, declared an emergency and stated the need for emergency equipment.

5. The local controller instructed flight 243 to change to the Maui sector transponder code to identify the flight. The first officer changed the transponder as requested. The flight was actually operating beyond the local controller's area of radar authority of about 13 miles. He therefore requested the flight to switch to 119.5 MHz (approach frequency) so that the approach controller could monitor the flight. Although the request was acknowledged, the flight was never heard on 119.5, but continued to transmit on the local controller frequency.

6. The captain slowed the aircraft down as he began approaching 10,000 feet mean sea level as required to comply with ATC speed limitations. He then retracted the speed brakes, removed his oxygen mask and began a gradual turn toward Maui's runway 02. As the airplane reached 210 knots, the crew could communicate verbally. The captain gave the order to lower the flaps.

7. Initially, the flaps 1 position was selected, then flaps 5. However, attempting to extend beyond flaps 5 led to aircraft controllability problems. The captain decided to return to flaps 5 for landing.

8. In addition, the captain experienced aircraft controllability problems below 170 knots. He therefore elected to use 179 knots for the approach and landing.

9. At the command of the captain, the first officer lowered the landing gear at the normal point in the approach pattern. The main gear indicated down and locked, however, the nose gear green indicator (gear position down and locked) did not illuminate. Manual nose gear extension was selected and still the green light did not illuminate, however, the red landing gear unsafe light was not illuminated either. After another manual attempt, the handle was placed down to complete the manual gear extension procedure. The first officer notified the tower that "we won't have a nose gear, we'll need all the equipment you've got."

10. While advancing the power levers to maneuver for the approach, the captain sensed a yawing motion and determined that the No. 1 (left) engine had failed. He tried to restart the engine, but there was no response.

11. A normal descent profile was established 4 miles out on the final approach even though the captain said the airplane was "shaking a little, rocking slightly and felt springy."

12. The airplane landed on runway 02 at Maui's Kahului Airport making a normal touchdown and landing rollout. The captain used the No. 2 engine thrust reverser and brakes to stop the airplane. During the latter part of the rollout, the flaps were extended to 40 degrees as required for evacuation. An emergency evacuation was then accomplished.

DECISION PROCESS ANALYSIS -- **With a large portion of the fuselage missing, the inability to communicate, high airspeed and rapid rate of descent problems, this accident demonstrates the need for a pilot's ability to process large amounts of both mental and physchomotor information and to be able to develop a meaningful pattern which somehow capitalizes on his training and experience.** The flap extension problem and engine failure later during the approach forced the captain to extend his level of competence to a multiple failure situation unique to the moment and respond to a series of "cues" based on the novel circumstances.

Furthermore, the captain's ability to continue with the normal aircraft procedural requirements during the approach (i.e., airspeed control, gear extension, descent profile, etc.) while assessing aircraft controllability and losing an engine demonstrate a high degree of self-discipline or self-regulation as well as a near instantaneous recall of the necessary training. Finally, the overall decision making process illustrates a positive, reasoned approach to an emergency.

CONCLUSIONS -- The magnitude of the accident was well beyond any anticipated emergency. The flightcrew's actions were consistent with simulator decompression training situations which minimize the exposure to physiological effects. The flightcrew's success in managing the multiple emergency situations and recovering the aircraft to a safe landing speaks well of their training and airmanship.

The following sections explore the literature on expertise in an attempt to understand the potential implications in developing appropriate training innovations. If the characteristics of expertise can be adequately defined and the cues which stimulate creative or opportunistic decisions identified, perhaps aeronautical training can be developed to accelerate the acquisition of those skills.

3.0 CHARACTERISTICS OF EXPERT COGNITIVE PROCESSES

Research on expertise and the differences between experts and novices is of great current interest and rapidly expanding into many areas within cognitive psychology and cognitive science (Gordon, 1990). Typically, the research approach has focused on expert performance in academic domains such as geometry, physics, engineering mechanics, etc. and employed psychometric testing methods to explore the different levels of cognitive processing. There is a real scarcity of information on outstanding individual performance or expertise in applied, real-world situations. Yet, this type of performance can be recognized in every day situations as diverse as financial markets (Wall Street decisions), emergency response medical teams (Chernobyl physicians) and aviation (the United Airlines flight 811 pilot/crew performance).

This section provides an overview of the conceptual cognitive psychology research that defines and delineates the important characteristics of expertise. The following section will elaborate and identify the implications of these characteristics in aviation. It is hoped that the understanding of the cognitive processes associated with "experts", will increase the awareness of these processes in the pilot training community. The importance of the attainment of a higher level of cognitive skills by pilots is the opportunity to enhance performance and further reduce human error accidents through improved decision making training.

3.1 Expertise

In virtually all arenas, a small group of individuals are recognized as exceptional performers. The abilities of these superior performers have historically been assumed to be the results of natural gifts or talent. Most of the research during the first half of the century (Guilford, 1967; Seashore, 1951 and Tyler, 1965) focused on the identification of these individuals with specific talents prior to the start of any long-term training. For most domains, this type of psychometric selection had very limited success in predicting which individuals would be superior or outstanding after training. Research in the last twenty years (Chase and Simon, 1974; Chi, Glaser

and Farr, 1988; and Lesgold, 1984) has revealed that superior performance is mostly the result of **accumulated skill and experience**. The primary differences between a beginner and an expert, as well as skilled performance at different intermediate levels, can be attributed to **acquired knowledge** and problem solving skills: what we call expertise.

Expert performance can be generally defined as the selection of an appropriate response to situations or problems in a wide variety of domains. As illustrated in Table 4, these might include selecting the best move in a chess game, correctly diagnosing a medical problem, or using the proper emergency procedure in aviation. The relevant research supporting this claim has focused on the basic understanding of *knowing how* to respond to a situation rather than *knowing what* rule-guided response has worked in the past. Intuition or know-how refers to an understanding that effortlessly occurs due to discriminations resulting from previous experience. Intuition is the product of deep situational awareness and involvement quite distinct from the conscious application of abstract rules (Dreyfus and Dreyfus, 1986).

Table 4 **EXPERT RESPONSES IN A VARIETY OF DOMAINS**

DOMAIN	SITUATION	EXPERT RESPONSE
Chess	A specific game pattern	Selection of the best move
Physics	A difficult problem	Solution generation
Medicine	Knowledge of a patient's symptoms and medical history	Correct diagnosis of the medical problem
Machine Repair	Description of equipment malfunction	Correct analysis & repair of the problem
Aviation	An impending emergency	Application of trained procedures or generation of appropriate response

During the last decade, expertise has been studied in a wide range of domains including: medicine (Patel & Groen, 1991), physics (Anzai, 1991), sports (Allard & Starkes, 1991), music and competitive games (Sloboda, 1991) such as chess and bridge. From this extensive research, a number of theories of expertise have evolved. A summary of the evolution and substance of these theories is presented in Appendix A.

The current theory of expertise is that a novice first solves problems by weak, domain general, heuristic methods (often working backwards from the goal); successful solutions (when repeated frequently) lead to the development of domain specific production rules and the beginnings of expertise; as these rules are used more and more often, and applied to many situations in a domain, they result in automatic generation of specialized productions which often use forward inferencing to progress from the initial problem state toward a solution or goal. Relative to the novice, the expert is able to reach the correct solution more quickly and efficiently.

3.2 Basic Traits of Experts

The status of the current theories of expertise are thoroughly summarized in "Thoughts on Expertise" and "On the Nature of Expertise" (Glaser 1986 & 1987). The latter reference, in particular, concludes with 24 "Summary Propositions" pertinent to this analysis. However, rather than simply restating this lengthy list or reviewing the entire two documents, the following summary of findings most relevant to aviation have been extracted.

1. Expert performance is characterized by **rapid access to a well organized body of conceptual and procedural knowledge**. Pilots are trained and tested in their ability to perform normal and "expected" emergency procedures. This training strengthens and expands their procedural knowledge base. High levels of competence result from the interaction between knowledge structure and processing abilities.

2. The organization of knowledge used by experts can be thought of as **schemata or a modifiable information structure based upon knowledge that is experienced**. This includes the interrelationships among objects, situations and events which individuals use to integrate and interpret instances of related knowledge. Schema theory assumes there are schemata for recurrent situations that expedite decisions in certain situations (e.g., the experienced pilot anticipating a thunderstorm by recognizing a threatening cloud formation, anticipating wind shear on landing, or anticipating in-flight icing conditions).

3. Expertise is domain specific. Within a domain, experts develop **the ability to perceive large meaningful patterns.** Furthermore, pattern recognition occurs so rapidly that it appears to take on the character of insight or intuition. This ability of experts appears to depend on the nature and organization of knowledge in existing memory which is directly related to training and experience. This is a partial explanation of how expertise, while domain specific, is characterized by the type of information processing of data within a domain.

4. Expert **knowledge is highly procedural and goal oriented**. Individuals with extensive domain knowledge are much better at relating events in cause-and-effect sequences that relate to the goals and subgoals of a problem solution.

5. The capability of experts to **fast-access** their knowledge facilitates problem perception in a way that leads to the **reduction of the role of memory search and general processing**. Although the novice and expert have equal capability for cognitive processing, novices typically use lots of search and processing in a less focused, more general manner. The outstanding performance of experts is derived from how their knowledge is structured for:

- Retrieval
- Pattern Recognition
- Inference

This expert capability is also referred to as "holistic discrimination and association". It manifests itself in the ability to intuitively respond to patterns without decomposing them into component features. This understanding occurs effortlessly due to discriminations resulting from prior, concrete experience.

6. Generalized thinking and problem solving skills may develop in individuals who acquire expertise in several domains (e. g., aeronautics, airplane systems, air traffic control procedures, emergency procedures, etc). **Continuous development of expertise in a field is based upon novel conditions that extend competence to novel situations.**

7. Experts develop specialized schemata that **match goals to demands of the problem**. Although both novices and experts can display good use of general problem solving process, experts use them primarily in unfamiliar situations.

8. The development of expertise is **influenced by task demands** encountered in the course of experience. In some domains, experts develop the capability for **opportunistic planning** which enables them to revise problem representations and to access multiple possible interpretations of a situation. These multiple patterns are quickly assessed and used to develop an "internal" visualization and then create a goal oriented scenario that can be played -- put in fine detail and in "slow-time" -- to a successful solution. In contrast, novices are less flexible and slower.

Experts build a mental representation of meaningful relationships in a situation. These relationships are more than the cognitive knowledge perceived by novices in the same situation. Long familiarization in a specific field of knowledge transforms the experts mental representations into an accessible form of **synthetic global knowledge** (Bastic 1982) which when applied to working situations has the characteristics of instantaneous insight or intuition.

9. Experts also possess metacognition abilities that are not present in less experienced decision makers. Experts develop **skilled self-regulatory processes** that free working memory for higher level conscious processing. These capabilities include: planning ahead, efficiently monitoring one's time and attentional resources, and monitoring and editing one's efforts to solve a problem. Self-regulatory activities become

generalized cognitive processes. These generalized processes become important when an individual is confronted with problems in unfamiliar areas.

10. An important point of distinction is that there are both routine and adaptive experts. Either type is outstanding in terms of speed, accuracy, and automatic cognitive performance. Either type can construct mental models convenient for performing their tasks. While both adaptive and routine experts are very confident in the execution of their solutions, routine experts have somewhat limited capabilities in dealing with novel or new problems. Adaptive experts, on the other hand, possess **the ability to creatively respond** to novel situations and develop an appropriate response with some reasonable chance for a successful outcome.

3.3 Routine vs Adaptive Expertise

The distinction between routine and adaptive experts, points to an avenue for the next generation of expertise research; this research will be from a cognitive psychology perspective and will stress applications to real world problems like how aviators respond to untrainable emergencies. A broad distinction between two classes of expertise is that expert performance involves "the reliable attainment of specific goals within a specific domain" (Sloboda, 1991). A more demanding definition is that "an expert is someone who can make an appropriate response to a situation which contains a degree of unpredictability" (Sloboda, 1991). Perhaps the most apt general characterization suggested that an expert is **someone capable of doing the right thing at the right time**.

In general, an expert will have succeeded in adapting to the inherent constraints of the task. If the task can be done most efficiently by forward search, the expert will search forward; if backward search is better, the expert searches backward. If certain patterns of cues are crucial to performing the task well, the expert will likely perceive and remember them; if patterns are not so important, the expert will not selectively process them. The tendency of experts to adapt to task constraints would account for the fact that whereas novices differ widely in the way they organize domain relevant concepts, experts tend to resemble each other (and differ from novices) in their conceptual organizations.

3.4 Time Pressures

The adaptive experts ability to form a creative, complete and integrated representation of complex problems is critical in real-world situations. The standard experimental paradigm has been to present a situation, e. g., sheet of information on a medical patient, a chess position, a scene from a basketball game, an electronic circuit diagram, etc., for a few seconds and then have individuals with different levels of expertise attempt to recall as much as possible. Novices can recall only a small amount. The amount of recall increases with expertise even at very high levels of expertise. In many cases, the recall of the super-expert is virtually perfect. Expertise in sports (basketball, land hockey, etc.), in games (chess and bridge) and in

computer science, electronics and medicine shows that the validity of the internal representation of the situation increases with expertise.

The ability to internally represent external situations appears to be related to the skill levels that experts develop to plan, i. e., mentally explore the consequences of potential sequences of actions even under extreme time pressures. There is a large body of informal evidence suggesting that this capability to plan increases with the acquisition of expertise. In domains where there is a pressure to respond rapidly often in response to dynamically changing situations, experts develop methods of coping with these demands.

The shortest possible reaction time to an external stimulus even after extensive training is about 200-250 milliseconds, and more complex reactions require between 500-1000 milliseconds. Research on elite tennis players, goal keepers in hockey and baseball players has shown that with increasing expertise, individuals dramatically improve their ability to correctly predict ball or puck trajectories relying on advanced cues. Similarly, typists, pianists playing from a score, and individuals reading text aloud are found to look ahead several characters, notes and words of material. This is referred to as eye-hand span. The size of the eye-hand span is closely related to level of expertise, such that expert performers have a long span and beginners or novices have essentially no span at all. The relevance of the eye-hand span in aviation is that it allows the expert pilot to scan the instruments while operating the aircraft controls, tuning radio frequencies, keying the microphone to talk to ATC, reading information off of charts, etc. In short, the expert pilot operates in an ultimate "multi-tasking" environment and needs highly developed eye-hand span capabilities in normal workload situations, and even more so in emergency situations.

These expertise domains which stress speed and solutions under time pressure may appear to always be driven by automatic responses to changes in the current situation. However the ability of experts to anticipate future conditions (such as the pilot's need to change aircraft heading or call ATC) and thereby reduce the need for responding to sudden changes in the situation implies an important role of an internal representation of the situation even in these types of expertise. Furthermore, the portion of the visual field that can be clearly seen at any given time is only a fraction (less than a thousandth) of the visual field, which means that monitoring the visual field and storing results in memory for later use and updating is a critical part of having an accurate description of the situation.

3.5 Expertise and Training or Practice

At the most general level, expert performance and expertise involves the acquisition of encoding processes allowing the situation (problem) to be fully represented and integrated internally in such a way that relevant actions can be retrieved from memory. The internal representation of external situations is also critical to planning and evaluation of possible courses of action as well as a means to

represent dynamically changing environment for the purposes of anticipation and prediction. The following paragraphs consider how this form of expertise can be attained and promoted by training and instructional activities.

As a first approximation, acquisition of expertise increases linearly in all relevant aspects of performance in a specific domain. The conventional use of categories to describe levels of expertise or phases of acquisition of expertise are shown in Table 5. Although knowledge about how experts acquire their expert performance is relatively limited, generally, the novice should have acquired all basic knowledge in less than one year. In parallel and continuing beyond this basic knowledge is the acquisition of problem solving skills where the knowledge is organized to effectively produce efficient performance. That is, there is an acquisition of the **procedural knowledge** of complex patterns occurring in specific domains. At this Intermediate level, differences in expertise appear to be related to the **cued recall** ability and the number and complexity of those patterns available for use.

Table 5 **PHASES AND CATEGORIES OF EXPERTISE**

PHASES OF EXPERTISE	CATEGORY OF EXPERT
Beginning Phase (Acquisition of declarative knowledge and domain general problem solving skills)	Beginner, Student, or Novice
About 1-2 years of active experience and training	Intermediate
Many years of active experience and training (Full time - 40-80 hours per week)	Routine Expert or Journeyman
More than 10 years of full time experience and training	Master or Adaptive Expert

Finally, in both the routine expert and adaptive expert categories, an accepted, domain specific vocabulary (or jargon) is developed to allow efficient communication among experts and masters in a given domain. This is obvious in medicine or law which also involve the use of Latin, French and to a lesser degree German. Similarly, in aircraft operations (from flight planning to air traffic control) experts have developed an extensive jargon which is formalized in the "Pilot-Controller Glossary" of the Airman's Information Manual. This manual is designed to promote efficient communications and a common understanding.

Most of our knowledge about how expert performance is attained comes from highly competitive domains with relatively vigorous evaluation procedures such as sports, games and music. Biographical analyses of the international level performers

in these domains show that they start early. By the age of seven most of them are engaged in instruction and daily practice. The amount of practice is gradually increased to about two to four hours daily during the early to late teens respectively. During early adulthood, these individuals spend virtually all their time on activities related to their domain of expertise. This amount of practice appears to be the single most important variable in determining the attained level of performance in a given domain. Athletes and expert musicians clearly distinguish practice as the most important activity for further improving performance.

Pilots, on the other hand, must practice for events that most likely will never occur. This creates a different expert training or development scenario. For example, attainment of expert status in aviation and other domains such as architecture, engineering and medicine appears to be the result of a slow accumulation of experience in "on-the-job" environments. Given the relatively unstructured nature of this "practice" and the relative infrequency of objective evaluation of performance or guidance by a master instructor, **improved performance and expertise in these fields relies much more strongly on the motivations of the individual**.

The following section describes the process of growth from novice to expert in the aviation domain and describes the implications of the growth in cognitive capabilities previously documented as they affect performance in that domain. Hopefully this preliminary examination will begin to provide insights into what kinds of training activities should be promoted to enhance the performance of individuals in these domains.

4.0 THE ROLE OF TRAINING AND EXPERIENCE

Thus far, we have documented and characterized the performance of experts from a cognitive psychology perspective. The overview of this field of research has shown that the development of expertise relies heavily on training and requires considerable amounts of experience in a specific field. Furthermore, experts rely on a wide variety of different processing skills and unique problem solving capabilities. As summarized in Gordon (1990):

1. Experts have more detailed, better organized knowledge structures.
2. Experts perceive and organize problems on a more abstract level than novices.
3. Experts perceive problems in large meaningful patterns related to the context.
4. Experts are much faster than novices because of their use of procedural knowledge and forward inferencing techniques.

All of these characteristics are equally applicable in the expert pilot domain and have been observed and documented in Section 2.3. At the same time, the past 15 years of aviation research in Aeronautical Decision Making (ADM) has developed training manuals (see Table 1, page 1) which teach pilot judgment as a two step, linear process (Jensen and Benel, 1977):

- The ability to search for and establish the relevance of all available information about oneself, the aircraft, the environment, the flight situation; to specify alternative courses of action; and, to determine expected outcomes from each alternative.

- The motivation to choose and authoritatively execute a course of action which assures safety within the time frame permitted by the situation.

Although this ADM training program has been successful in decreasing the number of accidents and incidents in the inexperienced pilot group (less than five years), it has not been as successful with the more experienced, high time, expert pilot group (Albert 1989, Alkov 1991). That is, their accident rate (accidents per 100,000 flight hours) has not been affected. At least one reason for the apparent shortcomings of ADM training is that it teaches a linear, algorithmic process of controlled decision making (see the Introduction for discussion). As we have seen in the foregoing analysis, this is not generally the way people make decisions, especially experts, and especially not in emergency or stressful situations.

In fact, a review of aviation examples (see Section 2.3) where expert pilots "saved the day" either in whole or in part, documented that pilot's making decisions under stress exhibit five basic characteristics shown in Table 6.

Table 6 **CHARACTERISTICS OF EXPERT PILOTS**

• REVERSION TO BASIC AIRMANSHIP SKILLS
• INSTANTANEOUS RECALL OF TRAINING
• REASONED APPROACH IN EMERGENCIES
• POSITIVE IN APPROACH & EXPECTATIONS
• SELF-ASSURED AND OPTIMISTIC

The following discussion explores the development of these expert pilot characteristics and attempts to relate that development to conventional training, experience, cognitive processing development and the new directions or innovations required for further improvements in decision making training.

4.1 Stages in Development of Pilot Cognitive Processes

For the purposes of the following discussion, it is important to note that human cognition is task dependent and purposeful (goal oriented). That is, humans use their knowledge, cognitive processing skills and the cues or stimuli of a situation or task to develop problem solving approaches. To accomplish this, two types of knowledge are used. These are declarative knowledge and procedural knowledge. Declarative knowledge consists of knowledge that can be verbalized, some call this knowledge about "facts and things". Procedural knowledge is knowledge about actions or how to perform various cognitive activities. These very often cannot be completely or adequately verbalized; for example, how to ride a bike could be broken down and described but the result would lose the essentials of the "how-to". However, procedural knowledge is the basis for development of specific steps (also called production rules) to be used in problem solving situations. As experience is gained, pilot's rely more and more on the use of procedural knowledge to solve problems. Furthermore they solve problems with increasing speed and accuracy using this type of knowledge as shown in Figure 2.

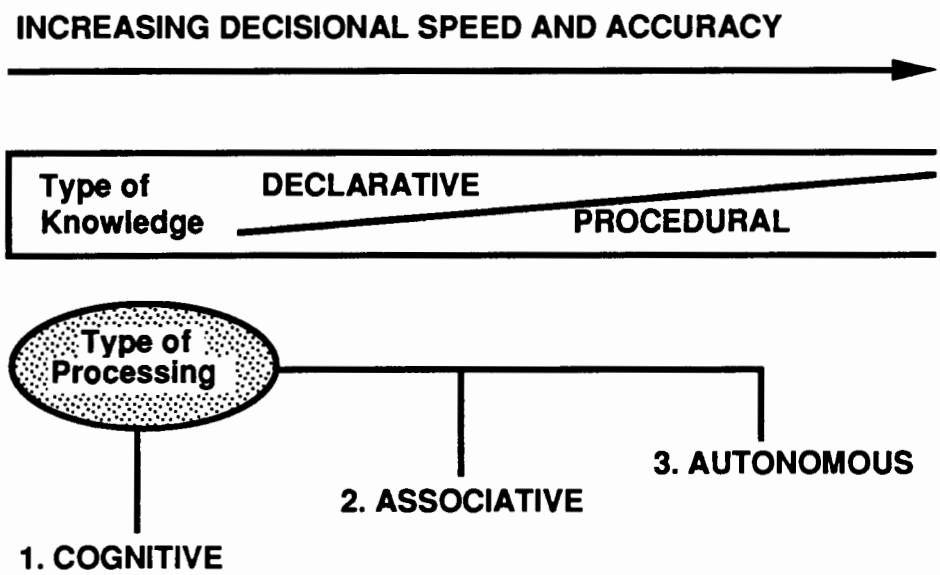

Figure 2 EVOLUTION OF EXPERT KNOWLEDGE TYPES AND PROCESSING TYPES

Cognitive psychology recognizes three stages in the development of expert problem solving skills (Anderson 1985) These are *cognitive, associative and autonomous* During the first, *cognitive* stage, pilots commit to memory a set of facts relevant to a desired skill. They typically rehearse these facts as they first perform the skill. For example, novice pilots learning stall recovery will memorize: recognize the stall, lower the nose, apply full power, level the wings and minimize altitude loss. In this stage, they are using their general aeronautics knowledge (domain-general) to guide their solution to loss of lift over one wing, and solve a domain specific problem, how to keep the aircraft flying. The problem solving capabilities and level of expertise in this stage are very basic. Novices spend a lot of time searching and moving around declarative knowledge.

The second, or *associative* stage, has two important characteristics. First, errors in the initial understanding and performance are detected and gradually eliminated. The novice pilot learns to coordinate the nose drop, power application and rudder application for a smooth stall recovery. Second, the connections between the various elements required for successful performance are strengthened. The pilot does not sit for a few seconds trying to decide which action to perform first after lowering the nose. Basically, the outcome of the *associative* stage is a learned procedure or production rule for performing a desired response to a known situation. In this stage, the declarative information is transformed and integrated into a procedural form. However, the procedural form does not necessarily replace the declarative knowledge. Rather the two forms coexist and are available when needed for the task. For example, the low time pilot can fly the airplane while simultaneously talking to ATC and navigating. All the while, he still remembers the rules of aerodynamics, the characteristics of a stall and the recovery process.

The third cognitive stage occurs when the problem solving procedures become faster and more automated. There is not necessarily any sharp distinction between the associative and *autonomous* stages of expertise. Rather, the *autonomous* stage evolves from the repeated application of known patterns and their associative use to achieve solutions. The use of declarative knowledge or "verbal mediation" often disappears during this stage of cognitive processing, at least for some tasks. In fact, the ability to verbalize knowledge of the procedure can be lost. Furthermore, expert cognitive process development appears to develop continually in a specific area or domain. Throughout the development, the skill gradually improves. **Ultimately, the skill can be extended to the ability to respond to cues not previously encountered and to develop new solutions or production rules applicable to novel situations.** The refinement of the expert pilot's cognitive processing and the characteristics associated with the three stages are illustrated in Figure 3.

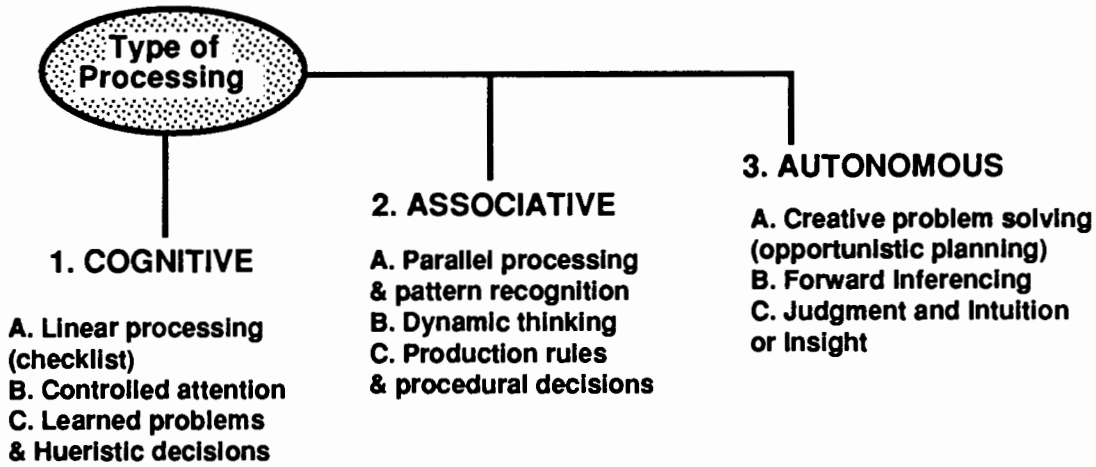

Figure 3 CHARACTERISTICS OF EXPERT COGNITIVE PROCESSES

4.2 Pilot Training and Information Processing

Conventional pilot training has been based upon this foundation: factual or declarative knowledge; flying procedures development; and, basic pilot skills or abilities as shown in Figure 4. The novice or ab initio pilot, therefore, is expected to learn: aerodynamics, airplane performance capabilities and limitations, electrical and hydraulic systems, Federal Aviation Regulations, etc. He is then trained in aircraft control and operation for both normal and emergency situations. This training includes a procedures development for preflight, takeoff, cruise, approach and landing phases of flight. Through this training, the novice develops and improves his basic psychomotor abilities and hones his flying skills. At this stage, judgment or decision making is only taught informally through training session debriefs, hangar flying, analyses of other pilots experiences and the limited flight

experience gained in preparation for an airman certification test. After successfully passing the test, the novice pilot is expected to cautiously begin developing good decision making and judgment skills as he gains experience. This provides the basis for the development of more sophisticated judgment as experience is gained.

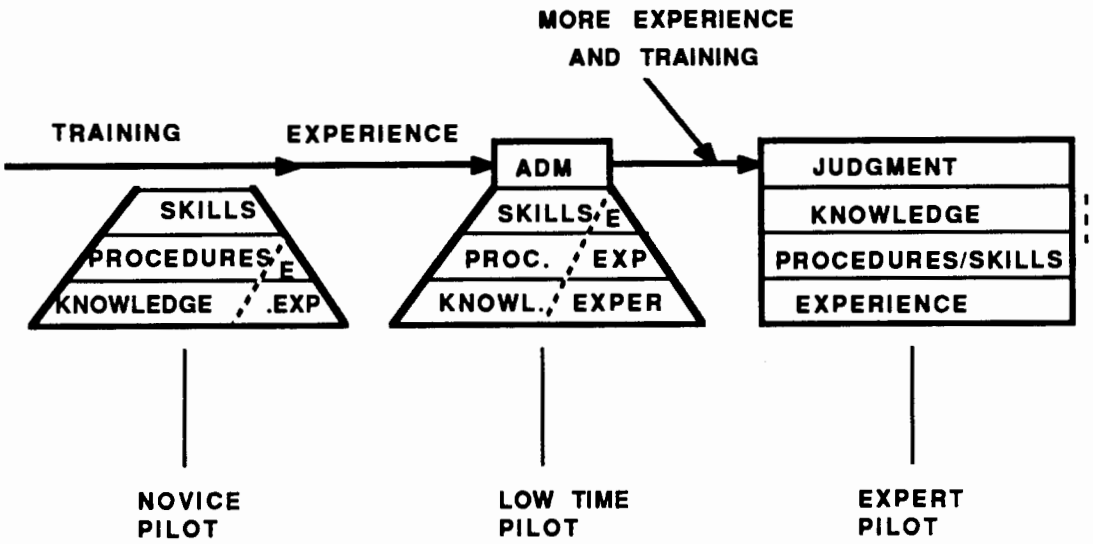

Figure 4 **CONVENTIONAL PILOT JUDGMENT DEVELOPMENT**

In aviation, training is highly procedure oriented both in developing flying skills (psychomotor) and in decision making skills (cognitive and informational) for normal and emergency operation of the aircraft. These procedures and skills provide the foundation for the development of more sophisticated production rules (procedural knowledge) as experience is gained.

The newly qualified or low time aviator (100-1000 hours) develops his flying and decision making skills through 1 to 5 years of experience. This experience allows him to expand his procedural knowledge base using encounters with real-world problems and operational constraints. At the same time, his decision making ability and cognitive processing is strengthened by repeated use of trained patterns and expanded associative networks of experience patterns. The low time pilot is at the second stage of cognitive process development; he has begun to develop the speed and quality of processing of the Routine Expert.

Finally, the Expert Pilot (1000-10,000+ hours) mainly relies on automatic cognitive processing abilities. Just as in the other domains of sports, games, music, and medicine, the Expert Pilot has achieved a tremendous base of procedural knowledge and skills applicable to normal day-to-day flying problems, trained emergencies (such as an engine failure) and novel or untrainable emergencies. He uses this

procedural knowledge base for a very high percentage of his problem solving and decision making just as the Routine Expert in other domains. In addition, he has the similar routine ability to retrieve and integrate information from his declarative knowledge base, if the situation requires that action.

The review of the case studies of expert pilot performance presented is Section 2.3, as well as NASA aviation research (Chappell 1991, Degani 1991) indicates that experienced pilots exhibit the "typical" characteristics of expert cognitive processes. Figure 5 illustrates the relationships between levels of pilot experience, types of knowledge used for problem solving and the three stages of development of cognitive processing ability.

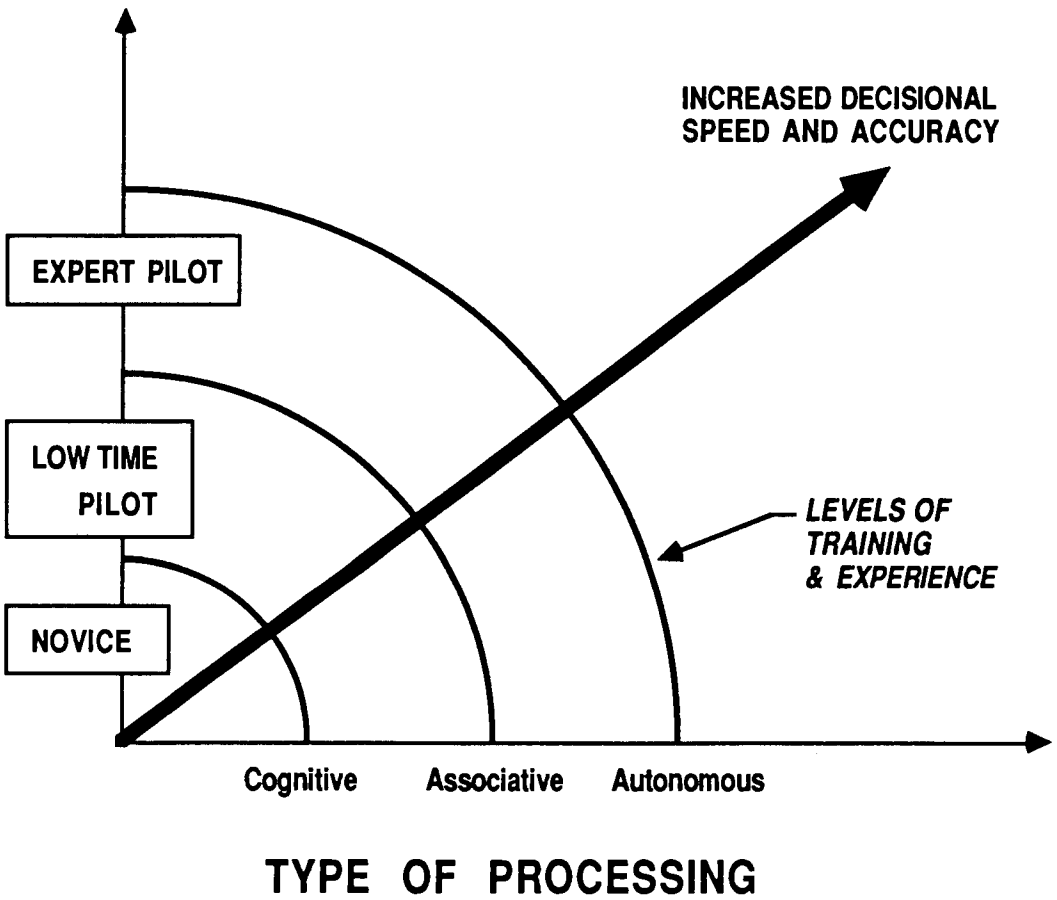

Figure 5 EXPERT PILOT JUDGMENT DEVELOPMENT

As shown in the figure, one main characteristic of the development of expert cognitive processes is the continual **increase in decisional speed and accuracy** as experience is gained in a specific area, e.g., aviation. In fact, these two characteristics

are precisely the areas of decision making and problem solving most affected by experience and training or "practice".

The three types of cognitive processing in the development of the expert pilot correspond to an increased use of procedural knowledge gained from both experience and training. The expert's cognitive processing which relies on recognizing known patterns and solving problems with automatic use of production rules or procedural knowledge corresponds to the conventional development from novice, to low-time, to expert pilot from a flying skills and aviation procedures perspective. This is an extremely valuable finding since it facilitates the understanding of the developmental relationship of cognitive skills with the development of aeronautical or aviation skills. **In fact, it could be argued that pilot training has included "expert" cognitive process training all along simply as a result of the strong emphasis on aviator procedures.**

To summarize: the novice or ab initio pilot responds (cognitively) to stimuli or external cues based upon a thorough understanding of a complex, declarative knowledge base. His decisions, whether normal or critical, are typically based on a linear problem solving approach (some type of checklist or "DECIDE" type of model). His capabilities are generally limited to the procedures he has learned and expedited by the use of rules-of-thumb (or heuristics). This type of cognitive judgment is somewhat restrictive, but usually successful, in its application to familiar tasks or problems. The novice is aware of the situational demands and reacts or responds to them, but with limited cognitive and analytical resources.

The low time pilot or (associative problem solver) has the capability for an enhanced decision making. As a result of his experience, additional flight training and possibly a knowledge of ADM principles, the pilot develops a capacity for more dynamic cognitive processing. At the associative level, he stores information in terms of schemata which are modifiable information structures based upon experience. The associative pilot uses pattern recognition and dynamic interrelationships among objects, situations and events to integrate and interpret related knowledge instead of the static, linear thinking of the novice. This level of cognitive processing is characterized by the early development of the capabilities of a routine expert in that certain large patterns are spontaneously recognized rather than requiring a conscious search of declarative knowledge and a checklist review of alternative solutions. The associative thinker is in the process of evolving into an expert in the general sense of his procedural knowledge and use of production rules, and, as stated earlier, it is difficult to draw a specific line of demarcation between associative and automatic problem solving.

4.3 The Expert Pilot

The Expert Pilot is "**adaptive**". In addition to having all the traits gained through experience and training, he can alter his procedures in real time (modify, delete or expand). He can create new rules and patterns based upon unique, previously

unencountered problem characteristics. This capability to creatively respond to unique problems or novel task demands identifies the highest level of expert pilot cognitive processes. In fact, the expert pilot's ability to adapt to task demands, set goals and retrieve solutions from memory occurs so rapidly it appears to be intuitive problem solving in many instances.

This "adaptive" capability is referred to as "KNOWING WHEN" (Dreyfus and Dreyfus 1986). That is, **the Adaptive Expert Pilot perceives the necessity to alter ingrained procedures based upon the parameters and dynamics (or cues and context) of the problem or situation encountered.** It is believed that this "KNOWING WHEN" (an almost direct perception of the proper course of action) may provide the key to the next generation of ADM training. This would require a training environment or "situation" that provided the necessary cues and context to trigger the expert's adaptive processing mechanism. Replicating the inflight kinesthetic cues using a simulator and the pilot workload cues using typical emergencies or Line Oriented Flight Training (LOFT) scenarios may not be sufficient to trigger the associative mental "hooks" or adaptive cognitive process.

Since experts store information as schemas or organized sets of facts, relationships and perceptions, these same schemas are a "major mechanism" (Anderson 1985) for problem solving either in the simulator or inflight. Therefore, the retrieval of information and problem solving procedures will improve the more closely the cues and context during training match the real "experience". The expert pilot's perception of the whole situation involves a sense of relations that include physical, cognitive and internal effects which are used to both store and retrieve knowledge. This is what was meant in Section 3.2 by the term "synthetic global knowledge" (Bastic 1982) used by experts for "opportunistic planning".

The coordinated use of cues and context with stored schema is believed to be a "major mechanism" used by experts to infer unobserved or unknown elements of a problem in "knowledge-lean" or "untrainable" novel situations. Delving into how experts develop insight into causal relationships in current situations by applying their global knowledge requires further understanding of the role of experience in cognitive processing skills development.

4.4 The Importance of Experience

Up to this point, the transition from novice to expert pilot has been shown to depend upon: the type of knowledge or knowledge structure; the type of processing that is used to effect a decision; and, the fast, accurate retrieval capability of proper actions. Specifically, high levels of cognitive processing, or expertise, were characterized by the predominant use of procedural knowledge and an autonomous processing ability. In addition, the performance of highly competent pilots indicates the ability to rapidly access and efficiently utilize their experienced based knowledge with marked increase in processing speed and accuracy, or appropriateness. These characteristics were seen to be based on an organized, modifiable knowledge

structure (schemata) derived from experience, whereas, novice pilots can adequately perform using methodical, heuristic thinking, their cognitive performance is limited by their inability to infer additional knowledge from the specific stimuli or cues of a particular situation.

In contrast to novices, experienced pilots can generate inferences in new situations based upon the cues and context of the specific task at hand. This forward inferencing capability is based upon: the content of their aviation knowledge structure; the procedural organization that experience has developed; and, the ability to go between the two and apply the proper solution for the current problem. The documented performance of highly competent pilots with extensive aviation knowledge bases in emergency "saves" provides a snapshot of the powerful problem solving abilities of human experts. These pilots have demonstrated the unique ability to utilize a large knowledge base in an efficient, automatic manner while simultaneously tailoring their decisions to the situational demands. The expert's cognitive processing can accomplish this with minimum reliance on time consuming search of declarative knowledge and heuristics compared to the less experienced pilot decision making techniques. Furthermore, the expert pilot can develop effective solutions in a "knowledge-lean" situation with ambiguous or contradicting information and in the presence of novel cues or task demands never before experienced. Therefore, a significant focus for understanding and training expertise will require additional understanding of how experience influences knowledge structures that are acquired over long periods of time, how experts normally use that structure and how that use can be altered to "adapt" to new problems.

As stated above, experienced pilots use more global pattern recognition, retrieval and inferences. These cognitive processes free-up working memory and improve the pilot's capability to plan ahead, efficiently monitor his time and attention resources, carryout the normal "housekeeping" tasks (i.e., aviate, navigate and communicate), and still leave time for emergency or unexpected decision making.

These expert traits are very similar to what is currently termed "situational awareness" and "cockpit resource management". Such characteristics and processes are strived for in all pilot training, but "experts" have the additional capabilities of self-regulation and editing or evaluating the results of decision making. These traits become generalized cognitive processes after pilots use them repeatedly.

Experienced pilots are highly procedural and goal oriented. As a pilot's information processing skills become more and more automatic rather than a controlled cognitive function, they tend to "experience" a situation and react to it rather than consciously analyzing and deciding. **Because they have experienced large meaningful patterns during daily flying situations, they are much better at relating events in cause-and-effect sequences to achieve their goals**. In other words, experienced pilot cognitive processes are like expert processes in other fields, at least in the extremely small amount of cognitive attention and conscious processing

required. Finally, these processes are fast, as the example accidents illustrated, and can be very effective in creating opportunistic solutions to new problems. Relationships are perceived, decisions made and actions taken so rapidly, that they take on the character of intuition.

Experiencing large global patterns repeatedly throughout an aviation career enhances a pilot's cognitive processing by providing redundancy or reinforcement of past similar situations, providing more associative paths to speed-up recall in new situations, and by providing elaborations or additional retrieval paths which can be used for both recall and inference. However, experience is more than developing and storing cognitive knowledge in context. As a pilot faces each flight situation, he adopts an attitude toward it based upon a multitude of external and internal "states". **This reaction or psychophysiological attitude includes kinesthetic, affective and cognitive components which comprise the "experience", form the basis of the experts "global synthetic knowledge" and provide the context and meaning of the situation to be used as a "mental hook" when needed for later decision making or problem solving.**

Experience can also interfere with the perception of a situation and provide negative reinforcement for later use of bad decision making. This is the case for some of the classic aviation accident cause/factors such as: "ducking under" Decision Height or Minimum Descent Altitude; fuel starvation/mismanagement; inadvertent IMC; etc. In many of the accidents attributable to these causes, the pilot or crew had repeatedly "gotten-away-with" bad decisions and consequently formed them into a bad behavior pattern. Past experience can also interfere with the perception of a situation through job or personal stress, anxiety, fixation, emotional blocking, etc. so that the synthetic knowledge which is stored will not be representative of the situation.

Therefore, past experience that is intended to be used for expert pilot cognitive processing development must insure perception of the essential psychophysiological elements of the problem so that this experience can be brought to bear in a manner appropriate to successful problem solving in new situations. In particular the importance of "conditioning" i.e., associating these global patterns of experience with specific responses appropriate to new situations has been shown by modern "Activity Based Learning" techniques. These techniques stress kinesthetic experiences with structural apparatus associating ideas with experiences that can later be recalled and used "intuitively" Once again, the appropriateness of the synthetic experience will be critical to the subjective associations between the elements of the situation and the schema/global pattern used to hold the solution in mind for later use.

5.0 RESULTS

There is substantial evidence in the aviation domain that verifies the "typical" characteristics of expert cognitive processes. Figure 6 was prepared as a final summary and integration of the progression from ab initio to experienced pilot and novice to expert decision maker. An important distinction in this progression is the transition from KNOWING WHAT to KNOWING HOW and ultimately to KNOWING WHEN (Dreyfus and Dreyfus, 1986).

The novice has all the knowledge base, skills and cognitive abilities to know *What* is required in normal decision making situations, and , given sufficient time can accurately determine the proper course of action. The low time pilot has begun to develop schema based knowledge and the characteristics of the routine expert. He processes knowledge faster using procedural techniques and knows *How* to react to a situation without excessive analytical processing of declarative knowledge.

In contrast, the expert pilot confronts new situations just as comfortably and competently as normal or routine situations. He uses his experience to deftly analyze the context of the moment and the available cues and stimuli to determine *When* a procedure should or should not be used. He has the "adaptive" capability to modify his procedural knowledge base and production rules almost instantaneously while maintaining the ability to consciously analyze and self-regulate the situation. This ability to infer the necessary actions and plan ahead, while freeing-up one's working memory to monitor one's time establishes a true plateau in pilot performance. It re-introduces the dimension of time into the decision making process. This self-regulation capability explains why time pressures seem less important in highly stressful situations and things often are reported to "slow down" during extreme situations. It is believed that this "KNOWING WHEN" may provide the key to the next generation of ADM training. As in the general field of expertise, isolating and quantifying the cues that experts use to either trigger a routine response or the mechanism to adapt remains a challenge.

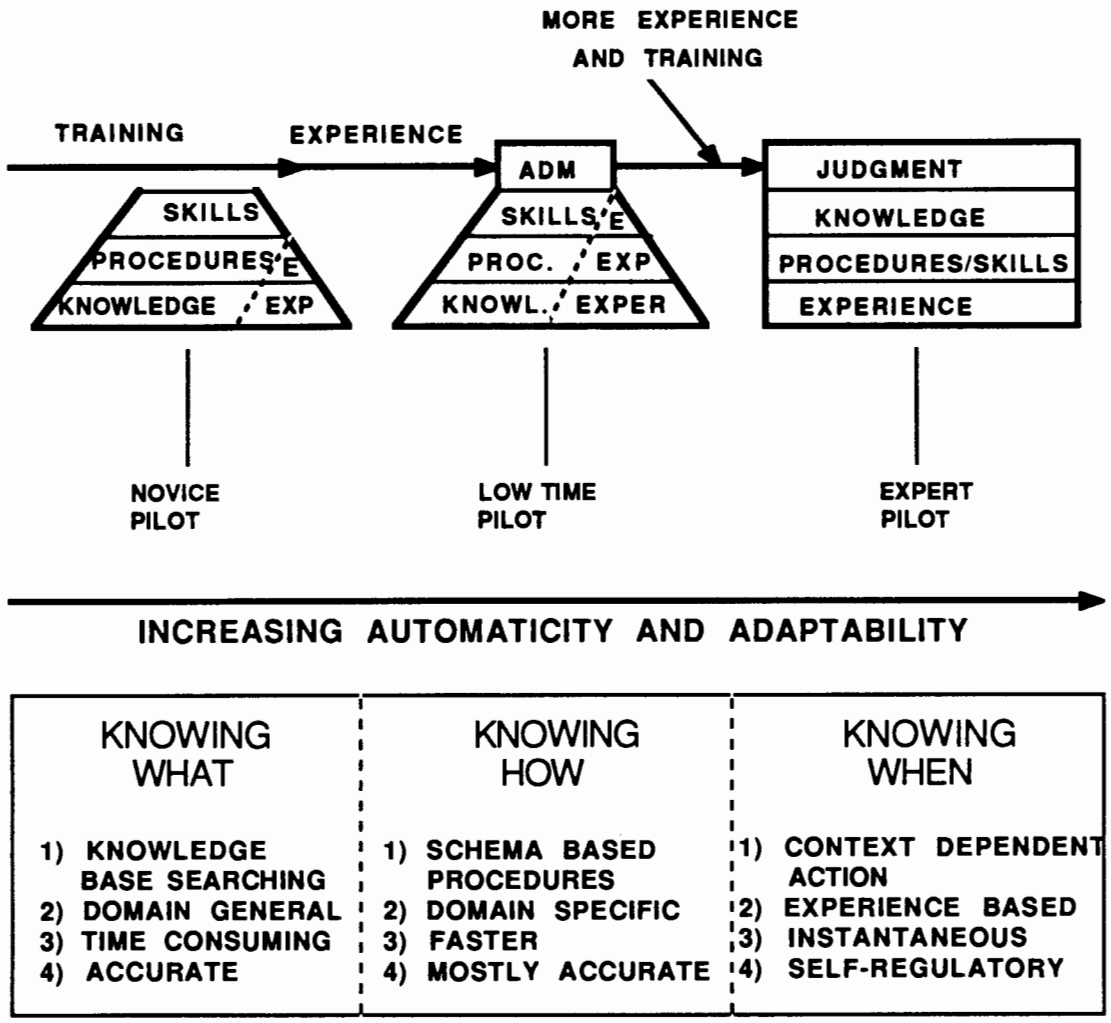

Figure 6 EVOLUTION TO ADAPTIVE EXPERT COGNITIVE PROCESSES

6.0 CONCLUSIONS AND RECOMMENDATIONS

The major conclusions of this initial study of the cognitive processes of expert pilots are:

1. **Expert cognitive performance is characterized by rapid access to a well organized body of conceptual and procedural knowledge.** This is a modifiable information structure based upon knowledge that is experienced. This experience allows the perception of large meaningful patterns in familiar and new situations which help the expert match goals to task demands. This means they can respond creatively or with opportunistic solutions based upon a global perception of the meaningful relationships in a situation.

2. **Experienced pilots have exhibited expert cognitive performance in keen, quick, confident decisions and almost a direct perception of the proper course of action which occurs so rapidly it appears to be a cognitive process and behavioral resultant based upon insight or intuition.** This intuitive performance is based upon: experience (cognitive and sensory, internal and external); the cues and context of the situation; and, the experts ability to identify causal relationships in a situation.

3. **The development of these expert pilot cognitive processes can be correlated with the typical growth in other aviator skills which result from training and experience.** The ability to develop a second generation of ADM materials to teach or train these skills will require a more thorough understanding of how experts use past experience to assess new situations, make decisions and define goals.

4. **The expert pilot is adaptive.** He can perceive the necessity to alter (on not to alter) ingrained conceptual and procedural knowledge based upon the parameters and dynamics (cues and context) of the problem or situation encountered.

5. **Experiencing situations repeatedly throughout an aviation career enhances a pilot's cognitive processing** by providing reinforcement of knowledge to apply to similar new situations, by providing more associative paths to speed-up recall of knowledge and **by providing elaborations on previous situations which can be used for both recall and inference.**

6. **Experience can also interfere with the perception of a situation and provide negative reinforcement for later use in bad decision making.** Job or personal stress, anxiety, fixation, emotional blocking, etc. will affect the stored knowledge negatively and it will not be usable in new situations.

7. **Experience or training that is intended to be used for the development of expert pilot cognitive processing development must insure the perception of the essential psychophysiological elements of the problem.** The appropriateness of the experience will be critical to the subjective associations and stored knowledge patterns that will be used in new situations.

In order to translate this introductory information on expert vs. novice pilot decision making characteristics into a set of useful tools and training techniques, a significant amount of additional research is required. **The recommended focus of this research should include the following areas.**

First, the understanding and explanation of expert pilot cognitive skills presented in this draft report needs to be reviewed and validated at several levels. The internal FAA review of this report will initiate the process. It is hoped that this process can be expanded to include a peer review by cognizant human factors and psychology personnel involved in civil and military pilot decision making training.

The second major analytical phase of this research would require validating the differences in expert vs novice cognitive processes with empirical data. This effort should analyze human performance error accident data both pre and post introduction of Aeronautical Decision Making materials developed by the FAA. This analysis should include an examination of the resistance to decision making training which have been documented in both civil and military pilot communities.

Finally, a major analytical effort would be necessary to begin to fully explore the non-linear modeling aspects of expert pilot cognitive processes, identify appropriate training alternatives and develop recommended training methods and tools for teaching expert decision making. Such an analytical project should include identification of any links between single pilot general aviation and airline (multi-crew) cognitive training requirements and the potential for developing cognitive processing measures suitable for both environments.

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APPENDIX A

SUMMARY OF EXPERTISE THEORY DEVELOPMENT

During the last decade, expertise has been studied in a wide range of domains including: medicine (Patel & Groen, 1991), physics (Anzai, 1991), sports (Allard & Starkes, 1991), music and competitive games (Sloboda, 1991) such as chess and bridge. From this extensive research, a number of theories of expertise have evolved.

Due to the limitations of space and time associated with this paper, it is impossible to thoroughly review the literature in detail. Therefore, the following discussion will be limited to observations and comparisons from a select few of the more prominent studies of the processes and knowledge that experts have acquired.

Early theories on expertise were centered on the conceptualization of problem solving as a search task of a declarative knowledge base (Newel and Simon, 1972). In particular, these studies noted that experts tended to use rules or shortcuts that were not universally correct, but that often helped, even if they sometimes failed. They hypothesized that specification of a small number of heuristic methods for linear search (for example, means-end analysis) could be applied across an indefinitely broad range of domains, with minimal knowledge about the specific content of any particular domain. The first fruits of these theories were in the area of artificial intelligence or expert (digital) systems. A prominent example of this work was the General Problem Solver (Anderson, 1985) which was an implementation of a computer based general method for heuristic search. These early theories about expertise can be summarized by characterizing an expert as someone particularly skilled at general heuristic search.

The heuristic search hypothesis was short lived. First in chess (Chase & Simon, 1973), then in physics (Chi, Feltovich & Glaser, 1989), and then in several other domains , it became apparent that expertise depended crucially on detailed domain knowledge, reflected in specialized memory abilities and forward inference patterns. Heuristic search methods were general, but weak, characteristic of novice rather than expert performance. Complex problem solving research in the second generation assumed that an integration of the basic human information processing skills was required. This included the processes of perception, memory, attention, and reasoning. In this context, the research assumed real-world importance since expertise obviously depended on learning how to do something well. The study of procedural learning rather than linear, declarative processing became a crucial area to be understood.

These theories of expertise provide a fundamentally simple picture of the development of expertise. The central idea (most clearly articulated in Holyoak, 1990) is that expert sequences that yield a successful solution to a problem can be

"stored" as new, tailored production rules that will lead to more efficient solution of similar problems in the future. This process can be viewed as an implementation of the hypothesis (Glaser, 1987) that expertise involves the acquisition of large integrated "chunks" of knowledge. In knowledge compilation, chunks take the form of larger, more detailed conditions and actions or production rules. Larger conditions or patterns provide greater specification of the precise circumstances under which the action is appropriate: larger actions allow more to be accomplished by a single "rule-firing". In addition, compilation involves a reduction in the need to access declarative memory, and an acceleration of rule-firing due to the strengthening of rules with each successful application. This process is closely related to the theory of the third stage of learning as "automaticity" (Anderson, 1985) which develops with practice in a specific domain.

The general theory of expertise at this point is that a novice first solves problems by weak, domain general, heuristic methods (often working backwards from the goal); successful solutions (when repeated frequently) lead to the development of domain specific production rules and the beginnings of expertise; as these rules are used more and more often, and applied to many situations in a domain, they result in automatic generation of specialized productions which often use forward inferencing to progress from the initial problem state toward a solution or goal. Relative to the novice, the expert is able to reach the correct solution more quickly and efficiently.