Methods and Principles for Determining Task Dependent Interface Content

Six-Month Progress Report at Year 1[1]

Submitted to
Kathy Abbott, Ph.D.
Human Automation Integration Branch
NASA Langley Research Center

by

Valerie L. Shalin, Ph.D.
SUNY at Buffalo
Buffalo, NY 14260

Norman D. Geddes, Ph.D.
Applied Systems Intelligence, Inc.
Gainesville, GA 30506

and

Brian G. Mikesell
SUNY at Buffalo
Buffalo, NY 14260

August, 1992

[1]This research was support by NASA Langley Research Center, under contract NASA-NAG11342.

Contents

List of Figures

List of Tables

Methods and Principles for Determining Task Dependent Interface Content

Valerie L. Shalin
State University of New York

Norman D. Geddes
Applied Systems Intelligence, Inc.

Brian G. Mikesell
State University of New York

1 Executive Summary

Computer generated information displays provide a promising technology for offsetting the increasing complexity of the National Airspace System. To realize this promise, however, we must extend and adapt the domain-dependent knowledge that informally guides the design of traditional dedicated displays. In our view, the successful exploitation of computer generated displays revolves around the idea of *information management*, that is, the identification, organization and presentation of relevant and timely information in a complex task environment.

The program of research described below leads to methods and principles for information management in the domain of commercial aviation. The multi-year objective of the proposed program of research is to develop methods and principles for determining task dependent interface content. These general methods and principles will:

- **Contain a clear partition between the contributions of the aviation task, specific aircraft equipment, human perception and cognition, and information management software to the design of an information display format.** Because of this partition, the methods lend themselves to straightforward modification in response to changes in aircraft equipment, making it possible to generate good displays without depending upon direct operational experience.

- **Be represented as a computational system.** A computational system ensures that the methods are executable, minimizes the role of unspecifed intuition, and ensures the completeness of the methods for the cases covered. Questions arising in the early implementations of the system help to focus experimental questions and aid in the intepretation of experimental results. When validated, the computational system can serve as an automated aid for interface design.

A prominent feature of the proposed methods and principles for determining interface content is the role of human intention in identifying relevant aspects of a task environment.

Geddes (1989) equates human intention with symbolic plans that guide both behavior and information search. Different plans correspond to alternative methods and tools for addressing what is apparently the same situation, and hence potentially identify different pertinent information. The use of plans to guide the identification of information requirements is referred to here as the *plan-based approach.*

The hypothesized role of plans as the basis of a method for identifying information requirements suggests a multi-year research program with the following objectives:

1. Refine the plan decomposition and parameter determination procedure, and establish methods for achieving useful decompositions and parameter values.
2. Empirically evaluate the feasibility of a plan based approach for the presentation of information, with respect to cognitive and engineering criteria.
3. Define and refine the grain size of plan-based information, and parameters for display, with respect to human interpretive processes.
4. Maintain and modify a computational system that translates plans into their information requirements.

1.1 Summary of Accomplishments at Six Months

The objective of the first year was to empirically evaluate the feasibility of a plan-based approach to the presentation of information. Our progress during the first six months with is briefly stated below, and discussed in more detail in section 4.0.

- Refine the plan decomposition and parameter determination procedure, and establish methods for achieving useful decompositions and parameter values.
  - A plan and goal graph for a part of the domain of commercial aviation has been developed. The current heuristic for decomposing plans, based on the differing requirements for information, was applied and continues to be appropriate.
- Empirically evaluate the feasibility of a plan based approach for the presentation of information, with respect to cognitive and engineering criteria.
  - The newly developed plan and goal graph demonstrates the relevance of the plan and goal graph concept for commercial aviation.
  - Relevant literature from Human Factors, Psychology, Computer Science, Engineering, Decision Sciences has been assembled and distilled into rules linking task properties and display requirements.

- A prototype set of presentation elements that provide for manipulation by an information manager has been constructed.

In the following section we identify critical issues regarding the management of information that must be resolved in order to develop the desired methods. This introductory information is followed by a detailed report on the progress achieved during the first six months of the program.

2 Statement of the Problem

The development of methods and principles for determining task dependent interface content for aviation operations is not a novel objective within the human factors community. The availability of computer generated displays and the increasing complexity of the National Airspace System have made this an important objective for quite some time.

Previous work conducted by Shalin and Geddes in this general area is discussed in detail in Appendix A. The following statement of the problem is developed in terms of the essential features of this work, revolving around the engineering goal of *information management*: the identification, organization and presentation of relevant and timely information in a complex task environment. Key issues include: The chosen unit of task analysis, cognitive theory regarding the selection and organization of information in real-world tasks, the appropriate grain size on both tasks and information, information management policies, and the substitution of domain-dependent common sense for insufficiently articulated display design methods and principles.

2.1 Plans as the Unit of Task Analysis

Webb, Geddes & Neste (1989) pointed out the problem of the chosen unit of task analysis. Webb *et al.* noted that the traditional unit of analysis is typically the *scenario* or *situation*. Since scenarios are too numerous to cover exhaustively, they are sampled for the purpose of display design, with the hope that displays designed with respect to the sampled scenario will transfer properly to unsampled scenarios in the operational environment. However, a given scenario may actually consist of a number of conceptually independent activities (e.g., handling an abnormal condition, contacting the company and flying the plane). A design procedure based on sampling a particular combination of activities risks permanent over-specialization of the displays to a relatively unique situation. Rather than risk this permanent over-specialization, Webb *et al.* recommend associating information with the individual primitive activities, and letting an intelligent information manager combine online the information to support the actitivities for a particular situation.

Geddes suggests that these activities are ideally regarded as *plans* addressing concurrent intentions (Geddes, 1989; Howard, Hammer & Geddes, 1988; Rouse, Geddes & Curry, 1987; Shalin, Geddes, Miller, Hoshstrassser, Levi & Perschbacher, 1990; Shalin, Miller, Geddes, Hoshstrasser, Levi & Perschbacher, 1990; Webb, Geddes & Neste, 1989). Plans consist of different operational methods, with different tools to achieve the same goal (Miller, Galanter & Pribram, 1960; Sacerdoti, 1977). The distinction between plans and goals as elements that comprise intentions allows for different operational methods—with different tools, and hence different important associated information—to achieve the same intent. Accordingly, the large set of information in the situation can potentially be trimmed down by knowing which of the alternative plans are in use.

Domain plans and goals at various levels of abstraction are organized by the *plan and goal graph* (Rouse, Geddes & Hammer, 1990; Sewell & Geddes, 1990). The plan and goal graph (PGG) represents a decomposition of the most abstract purposes of a system into increasingly resolved descriptions, until the descriptions are completely composed of primitive (i.e., directly executable) actions. Multiple uses (or parents) of plans and goals results in a directed acyclic graph.

A portion of the plan and goal graph in the domain of commercial aviation, developed during our the first six months of research, is illustrated in Figure 1. The graph represents a decomposition of the most abstract purposes of a system into increasingly resolved descriptions, until the descriptions are completely composed of primitive (i.e., directly executable) actions. Plans are represented by rectangles and goals are represented by ovals.

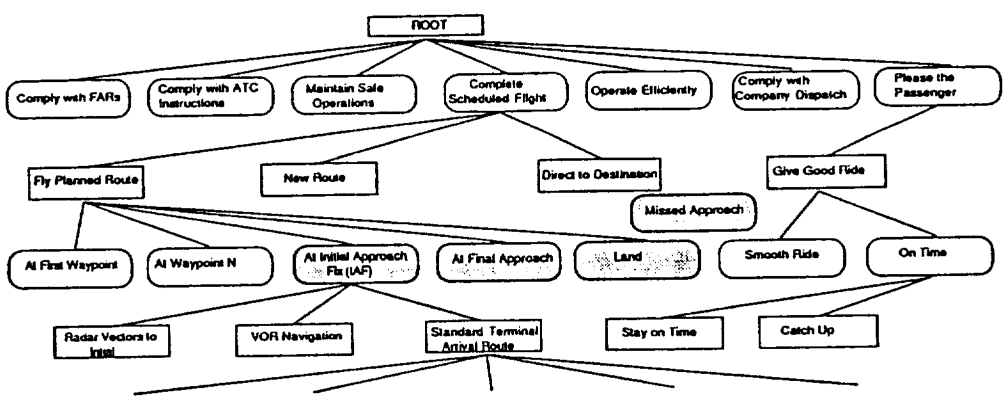


Figure 1. A portion of the plan and goal graph analysis for commercial aviation.

2.2 The Selection and Organization of Compatible Information

Structuring the task environment according to the activity one intends to perform is the essence of ecological approaches to perception (Gibson, 1979; Vicente, 1990; Vicente & Rasmussen, 1990.) The real-world cognition involved in flying an airplane depends essentially upon sampling and organizing information from an indefinitely large context (Geddes, 1989). The available information can be selected for relevance to the current plans, thereby inverting the typical claim from within the Cognitive Science community about the relationship between problem information and the knowledge structures in human memory. Typically an analysis of the information in the problem statement in limited laboratory or schoolbook tasks *guides the definition of cognitive structures* (Chi, Feltovich & Glaser, 1981; Larkin, 1982; Greeno, 1983; McDermott & Larkin, 1978; Paige & Simon, 1966;).

However, we ought to be able to examine cognitive structures defined on some other basis, to guide the identification of *related features of the external problem situation* (Chase & Simon, 1973).

Having hypothesized plans as the appropriate unit of analysis, information for display therefore corresponds to tests of features of the environment that aid in the selection, execution and monitoring of plans to alter an undesirable state, or cause a desirable state to persist. Hypothesized information requirements for the Autopilot Speed Capture plan are shown in Figure 2. [1]

2.3 Plan Grain Size

Adopting plans and their arguments as a framework for determining plan information needs does not define a complete approach to information management. Methods and principles for determining task dependent interface content require a proper grain size on plan descriptions so that they capture differences in the information associated with different plans, as well as the cognitive phenomena associated with the interpretation of information. Moreover, once a grain size is determined, cognitive compatibility issues must now be considered for multiple concurrent or sequential plans, alternative plans, and the computational demands on the information management process.

2.4 Information Management Policy

The introduction of information management software makes explicit the potentially tacit notion of an information management policy governing display configuration. Information management policies should be formulated in response to the particular information problems that are expected in the application domain. The kinds of problems associated with information have been classified by LaRC as the following:

- information access
- information perception
- information interpretation
- information deprivation
- information application to task
- information prediction

[1] The intended connotation of *requirement* is closer to LaRC's concept of *desirement* than the word implies.

The information management policy under investigation by this project addresses problems of access, perception and interpretation. It can be described as a "greedy" approach that seeks to provide as much important information across all concurrent plans as can be presented, while tailoring the presentation form and location to facilitate perception and interpretation. This policy is particularly well suited for task domains in which the information user is generally well-supported with available information and well-trained in its use, but is under time constraints to access, perceive and interpret the information. This circumstance is common in aviation, but the policy may not deal with all information problems in the domain.

Goal: Observe Speed Restriction
Plan: Autopilot Speed Capture
Set the autopilot mode
Arm the speed capture
Set the desired speed
Monitor engine parameters
Monitor speed change

Information Requirements:
Autopilot mode
Autopilot status
Current speed
Speed to be captured
Current altitude
Altitude at capture
Altitude remaining to capture
Vertical speed
Current DME
DME at capture
Distance remaining to capture
Navigation radial at capture
Navigation facility defining speed restriction
Engine thrust setting
Spoiler extension state
Pitch attitude

Figure 2. A plan and its information requirements.

The information management policy incorporated into an information management system impacts the methods for identifying task information requirements because the dimensions manipulated by the information management system must be supported by an appropriate set of attributes associated with the information for display. The following parameter values are manipulated under the current information management policy, to constrain the display of the information to be compatible with pilot reasoning.

- The importance parameter—indicates the relative importance of the information, given limited display real estate.
- The bandwidth parameter—indicates how frequently the value of an information element changes by an operationally meaningful amount, and hence, how frequently its displayed value will require updating.
- The resolution parameter—indicates the requirements for fine distinctions between states.
- The scope parameter—indicates the range of possible states that must be in view at any one time.
- The control parameter—indicates the pilots need to control the value of an information element, constraining the display of the information to be coincident with an input device.

Some of these parameters have already been manipulated in the design of dedicated displays. For example, the resolution on the dial for Indicated Airspeed is unevenly represented on the MD80, with the distance and number of tick marks between 250 and 300 equal to the distance and number of tick marks between 240 and 250. Abbott (1989) describes a display element developed by Boeing for 757/767 engine parameters that combines a dial without tick marks and a digital display, to complement the tradeoffs in scope, resolution and bandwidth that each component embodies. In both cases of display element innovation, we presume the designer was attempting to accomodate very different activities with one device. With computer generated display elements, we now have the option of adjusting the display element in question for the task at hand.

Figure 3 illustrates the some of the parameter values for the Autopilot Speed Capture Plan. In contrast, if we were displaying information for a different plan to achieve the same goal, these parameters might change. For example, the pilot might Observe the Speed Restriction by effecting a Manual Power Change. The essence of this new plan is controlling, rather than monitoring, which is known to place different demands on pilot information processing (Harris & Spady, 1985; Abbott, 1989). We would make several adjustments in the parameters controlling the presentation of current speed information, increasing both its resolution and bandwidth, while reducing the parameters describing Autopilot information.

Goal: Observe Speed Restriction
Plan: Autopilot Speed Capture
Information Requirements:

Autopilot mode	
importance	10
scope	3
resolution	3
bandwidth	2
control	10
Autopilot status	
importance	10
scope	2
resolution	1
bandwidth	8
control	0
Current speed	
importance	10
scope	4
resolution	7
bandwidth	4
control	2
Speed to be captured	
importance	10
scope	2
resolution	7
bandwidth	2
control	10
Current altitude	
importance	5
scope	5
resolution	2
bandwidth	3
control	1

....

Figure 3. A Selection of parameterized information requirements.

We can imagine the need to add to the existing dimensions of the information management problem. For example, information management based on information timeliness or age is not a part of the current information management policy. Of course, adding such a dimension to the information management system necessitates changes to the methods of analyzing plans for their information requirements.

2.5 Information and Presentation Element Granularity

The information elements in Figure 3 indicate the contents and display parameters for what is to be displayed. They do not, by themselves, define a specific format. Formatting is accomplished by matching capabilities of specific *presentation elements* with the contents and parameter values of information elements. Information management policy is necessarily reflected in the granularity of presentation elements; The granularity of presentation elements sets an upper limit on the ability of the information manager to adapt the presentations to meet the information needs of specific tasks. In addition, presentation elements are characterized by a set of attributes that represent the available manipulations of the information manager. The granularity of these attributes limits the extent of information management. Coordination of the granularity of the presentation elements and their attributes with the information requirements and attributes is essential to realizing a visible effect of information management in the final display; A mismatch in granularity results in needless computation.

2.6 Towards a Theory of Task-sensitive Display Design

The persisting role for the operationally knowledgeable display designer (also noted by Abbott, 1989) may be regarded as a clue that domain-dependent common sense is informally, and indeed often successfully, substituting for insufficiently articulated display design methods and principles. It is our hypothesis that the ability of the operationally knowledgeable designer to successfully develop display designs is due at least in part to a well developed, internalized set of operational principles or *domain theory.* One part of this domain theory links the task, equipment and human cognition to abstract, parameterized information requirements. This part of the domain theory is depicted in Figure 4. A second part of this domain theory exercises implicit knowledge about the perception and interpretation of display media features to link parameterized information requirements to presentation elements. Analysis of the underlying phenomena of perception and cognition of display features is expected to depend on a similar domain theory for presentation elements that predicts the interaction of an observer with a set of display features.

In both cases, the domain theory provides an explanation of existing information and presentation elements in terms that the information manager can use. While the domain theory does not serve as a generative mechanism for novel information or presentation elements, it is able to generate explanations for unanticipated elements. Although respecting a similar—but tacit—domain theory, the operationally knowledgeable designer may be unable to predict the implications of new systems, and in any case, is subject to the ordinary human limitations in such complex reasoning. Moreover, continued reliance on a knowledgeable designer allows this underlying theory to remain tacit, and impossible to test scientifically. The risk of an untested, unarticulated theory is the development of inconsistently successful methods, with poor transfer to new situations.

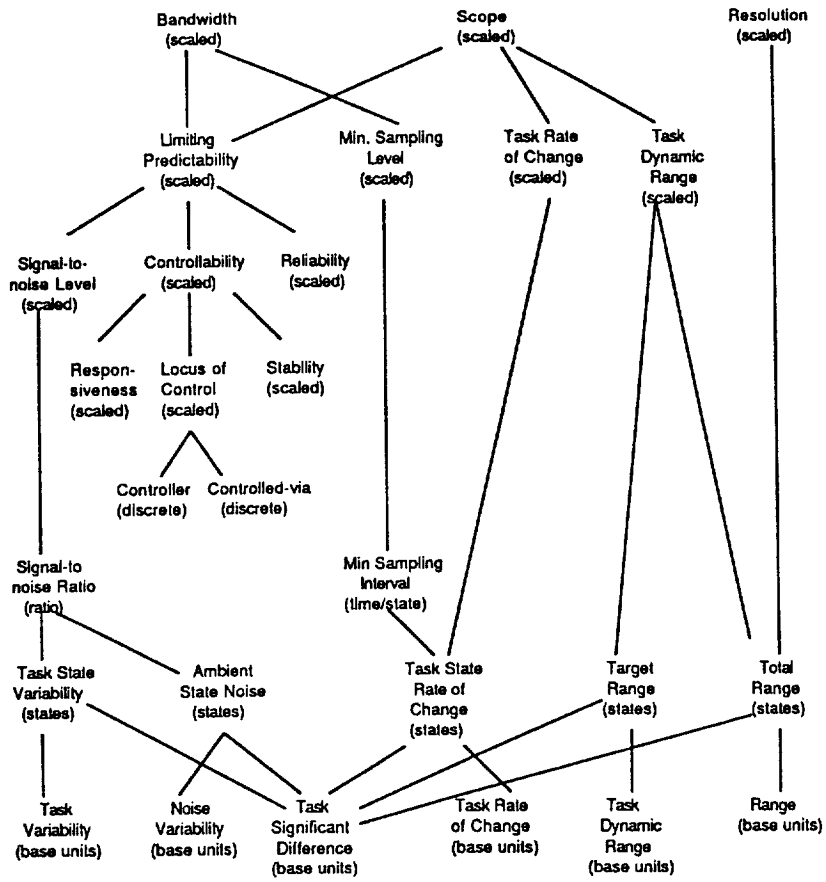


Figure 4. Attributes of information that determine parameter values for information management.

2.7 Implications of Previous Work for the Development of Context Sensitive Displays

Existing methods developed by Shalin & Geddes are plan-based, account for some of the cognitive processes of the pilot, as well as the dimensions of information management used by the system, and are formalized in a computational system that explicitly represents the domain theory. As illustrated in Figure 4, these methods make use of low-level task-dependent and task-independent pararmeters that describe the behavior of a particular piece of information in the context of a task. Thus the determination of task sensitive high-level parameter values for information (i.e., Scope, Resolution, Bandwidth and Control) has a sound theoretical foundation captured by the figure, but requires validation and testing with commercial pilots in an operational context.

The link between presentation elements and their parameter values has been the subject of considerable theoretical and empirical study (Spoehr & Lehmkuhle, 1982). The primary deficit of this work for the present purposes is that it has not been integrated into a set of coherent, rule-based claims about pilot performance in an operational context. Work on this task was initiated in Year 1 of this project.

Note that we have not identified the *correctness* of the domain theory as a critical assumption in this project. Rather, the critical feature is to have any theory that has empirical entailments (Carroll, 1991). The theory can always be modified in light of new findings, and the relevance of new findings is clarified by the context of the existing theory.

3 Approach

First, we must operationalize our existing theoretical analysis of the relationship between displays and plans, by developing an appropriate empirical methodology. The existing methods are now being validated in Year 1, by using them to define an interface and produce a knowledge base for an information management system, and examining part-task pilot performance. Second, we must extend the empirical methodology to new part-task studies, to validate its adequacy. This constitutes the basis of the Year 2 work, using the method-generated display, and variations in information management policy. Finally, we must apply the methodology to demonstrate the performance impact of plan-based information management. This evaluation will be planned during Year 2 and conducted during Year 3 at Langley Research Center.

The results of the empirical work will be used as support for specific aspects of the computational method, or to refine and recode the method as necessary. Some of the issues that will certainly be addressed include defining the useful level of plan decomposition for the information management problem, and the tradeoffs associated with various levels of information granularity. Potential areas of change include:

- Dimensions of information management
- Plan decomposition and granularity
- Event set
- Information granularity

4 Accomplishments at Six Months

The first six months of the project have been devoted to operationalizing our existing theoretical analysis of the relationship between displays and plans, with the overall goal of determining the appropriateness of plan-based information management. This included an extension of the methods, and the development of an appropriate empirical methodology.

4.1 Laboratory Preparation

This task involved the installation of a SPARC2 graphics engineering workstation at SUNY Buffalo, including connection to the local network, and printers and the installation of Unix, Common Lisp, C, and Hoops graphics software. The Graduate Research Assistant learned to program the graphics software for use in the development of the experimental data presentation software, and began programming some of the functions required for display management. The display generation capability at 6 months creates parameterized presentation elements and logical devices, assigns data sources to these objects, updates the data source according to a simple function, and allows for the manipulation of presentation elements according to Scope and Resolution parameters.

4.2 Analysis of Existing Data

4.2.1 Demonstrate the existence of plans

Existing data were potentially informative about the feasibility of plan-based information presentation, and the specific scenarios in which feasibility might be easily and clearly demonstrated.

Three researchers willing to provide existing data were identified: 1) Dennis Beringer, at New Mexico State University, who has been examining alternative 3d and 2d means of encoding altitutde information for collision aviodance; 2) Phil Smith, at Ohio State University, who has been examining crew information requirements during replanning scenarios; and 3) Bill Corwin, at Honeywell Systems and Research Center, who, along with V. Shalin and J. Bloomfield, conducted verbal protocol studies of information use during various take-off, landing and engine failure scenarios. Honeywell provided transcripts of its verbal protocols, and these were used in formulating an initial plan and goal graph for the studied portions of the commercial aviation task domain.

4.2.2 Method

Subjects— Four training pilots from McDonnell Douglas participated in the study as part of their assigned work. The same pilots typically served as instructors to airline pilots. One of the experimenters (B. Corwin) served as a First Officer. A McDonnell Douglas employee served simultaneoulsy as the simulator operator, Air Traffic Control and Ground Control.

Apparatus— The study was conducted in a fixed-base, six-degree of freedom simulator of the MD-80, operated for rental by FlightSafety International for training purposes.

Procedure— Each pilot performed several take-off, level flight, engine failure and landing episodes, in the simulated Los Angeles Airport environment under night conditions. In a manipulation unrelated to the purpose of this paper, some of the flight instruments were obscured from pilot view. Two experimenters, in addition to the First Officer, attended the experimental sessions. Pilots were instructed to "think-aloud" and all flight deck events were audio-recorded during a two-hour experimental session (Bainbridge, 1974; Ericcson & Simon, 1986). This audio record was transcribed and analyzed.

4.2.3 Analysis & discussion

Our analysis of the data collected by Bloomfield, Shalin & Corwin (1990) is encouraging.[2] A portion of the plan and goal graph developed from these data was presented earlier, in Figure 1. The remainder of the plan and goal graph is presented below in Figures 5a, b and c.

These figures illustrates several of the domain properties that support the use of a plan and goal graph in information management. These properties include:

- A plan abstraction hierarchy
- The interleaving of plans over time
- Subactivities shared by higher levels of abstraction
- The activity of plan evaluation by the crew
- The participation of multiple agents in plans
- Requirements for plan granularity

[2] Applied Systems Intelligence, Inc., is developing a protocol analysis software tool to perform the plan-goal graph interpretation of protocols.

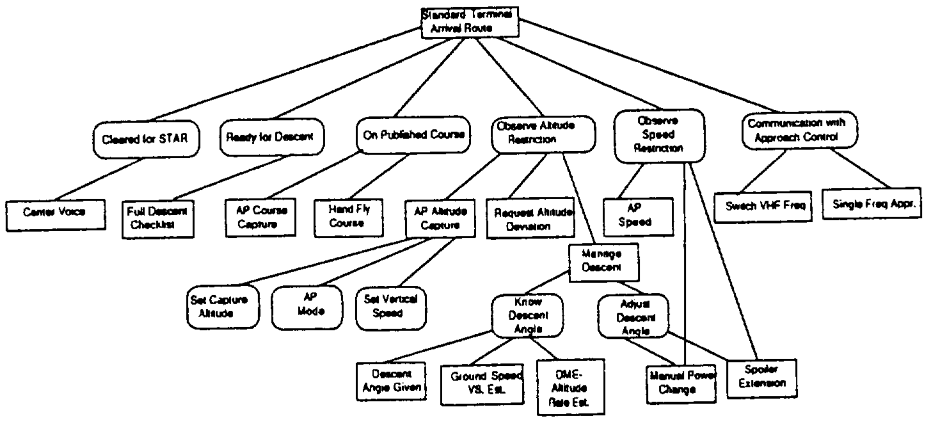


Figure 5a. The plan and goal graph for commercial aviation (cont.)

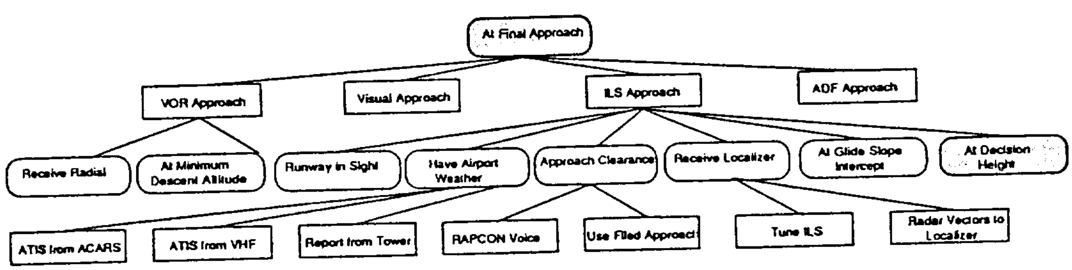


Figure 5b. The plan and goal graph for commercial aviation (cont.)

A Plan Abstraction Hierarchy— Pilot discussion can be organized according to the levels of abstraction of the plan-goal graph. The data illustrate two important points. First, pilot comments address all levels of the abstraction hierarchy. Second, several of the goals in commercial aviation are associated with multiple plans for achieving them (Rouse, Geddes & Hammer, 1990; Sewell & Geddes, 1990). Figure 6 pertains to the descent phase of flight. Several of the goals are associated with multiple plans for achieving them. For example, the goal to *Observe Speed Restriction* may be achieved by using the Autopilot, by a Manual Power Change, or by Extending the Spoilers. Evidence for all three occurs in the protocols.

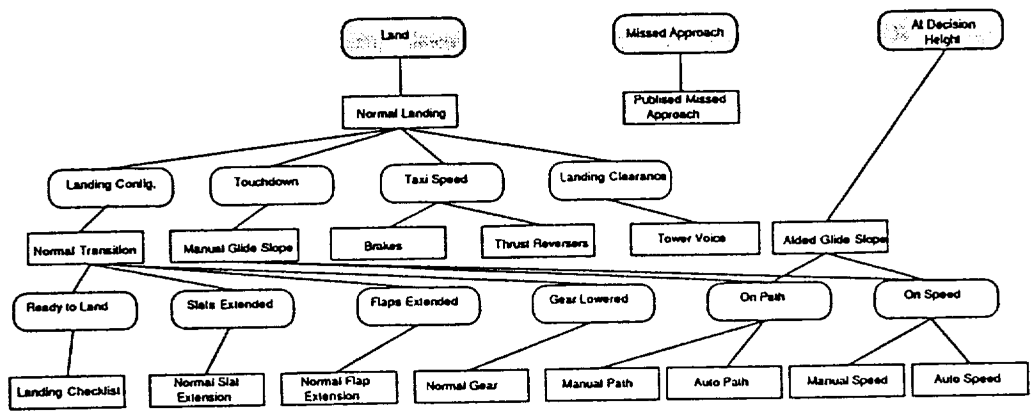


Figure 5c. The plan and goal graph for commercial aviation (cont.)

One of the important implications of identifying different methods for achieving the same goal is that the different methods potentially require different, and differently organized information. In this regard, note that the pilot mentions two options for accomplishing the goal of knowing his descent angle, by using DME-Altitude[3] Rate Estimation, or Ground Speed-Vertical Speed Estimation:

[3]DME refers to Distance Measuring Equipment.

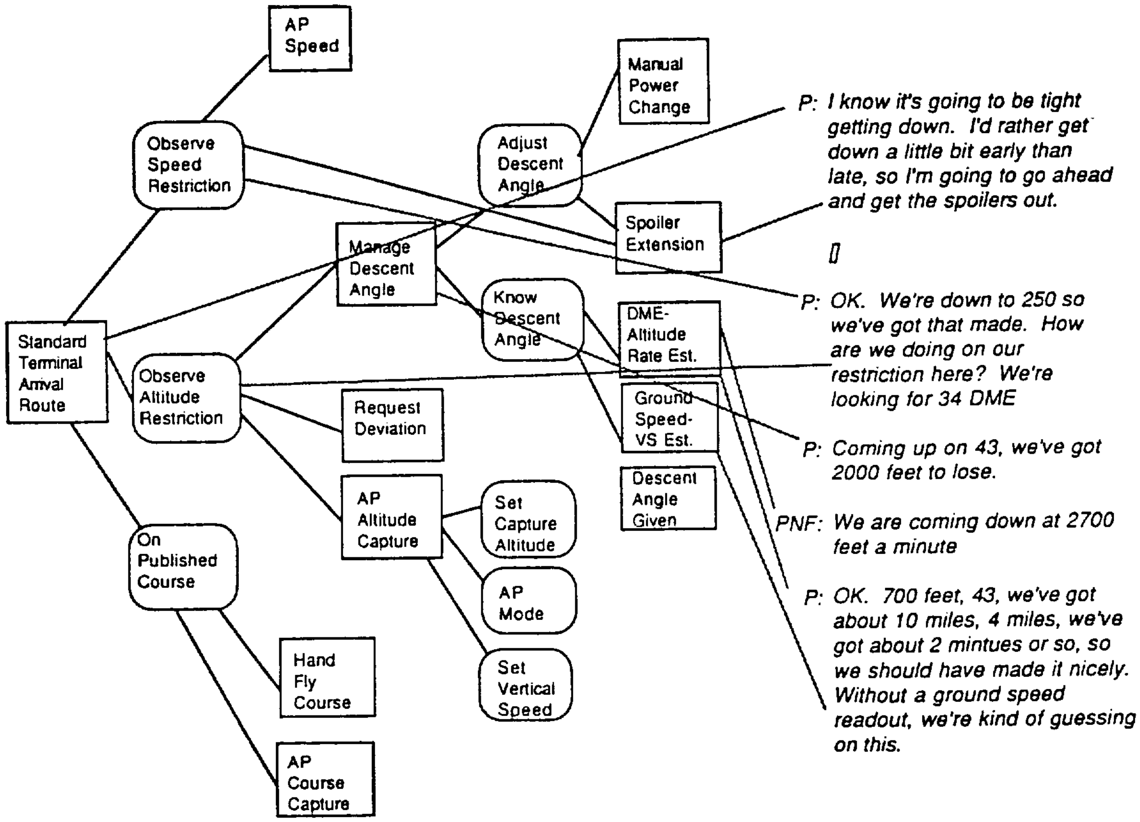


Figure 6. An illustration of the plan abstraction hierarchy.

The Interleaving of Plans Over Time— The concept of a plan-goal graph is also important for deciding when to present information. The sequencing of conceptually independent activities, even in well structured domains, is very difficult to script. The pilot protocols evidence many examples such as Figure 7, in which active goals are being addressed from many portions of the plan and goal graph.

The precise sequence of activity is driven by external events and convenience (Suchman, 1987). Consequently, timely information management will require an ability to determine on-line exactly which plans and goals are active (Geddes, 1989).

There is considerably more to be said about timing and information management from the perspective of plan-goal graphs (see below).

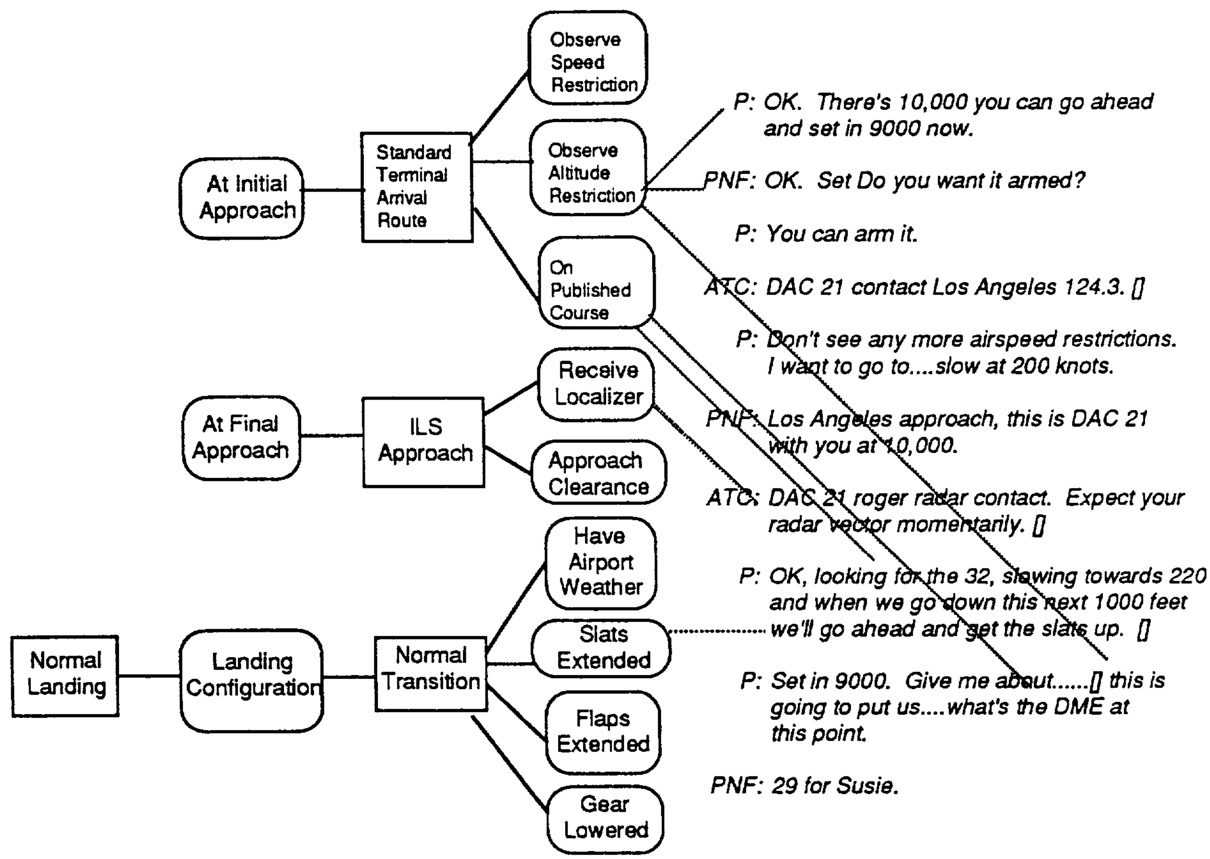
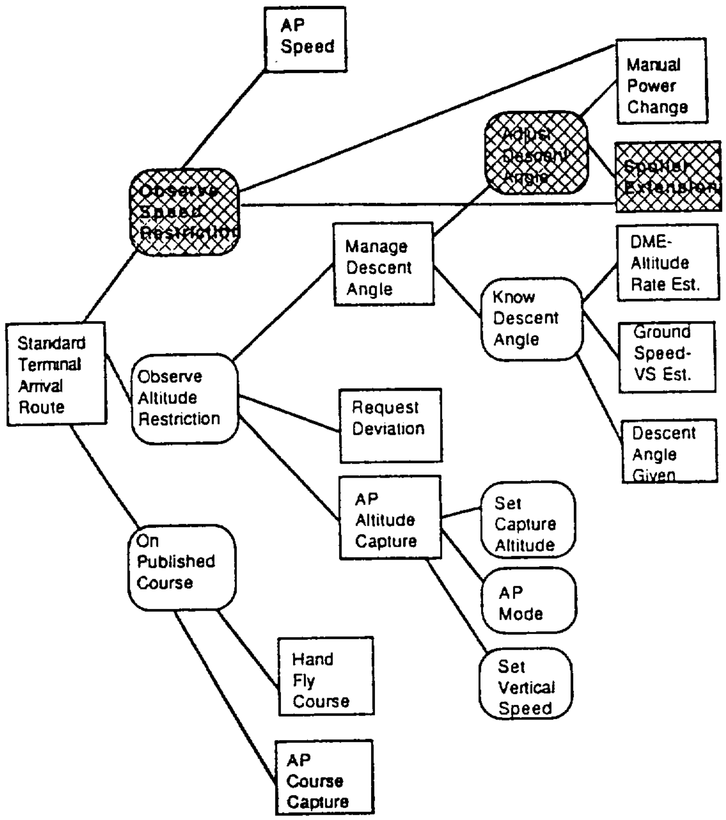


Figure 7. Interleaved active goals and plans.

Subactivities shared by higher levels of abstraction— The same plan may serve multiple goals in the plan and goal graph, and there is no requirement for these goals to be at the same level of decomposition in the graph. Figure 8 illustrates a portion of the plan and goal graph in which two plans serve as means to achieve two different goals. Although the first goal is achieved (Adjust Descent Angle), the pilot decides to retain the plan in service of the second goal (Observe Speed Restriction).



P: I'm looking at the flight director, I'm watching....got about 2,000 feet to go. The CDI is centered and we still got about 3,000 feet per mintue descent, so we're looking real good for the descent.

PNF: We're almost to 11,000.

P: Speed on 200, so when we level off it will start going towards 200. Ok. 700 feet to go. Now I am watching the flight director give me a nose-up indication warning.

PNF: We still have the spoilers out.

P: Spoilers out. That's OK. We'll leave them out until we get down to 200 knots.

Figure 8. Shared subactivities.

The activity of plan evaluation by the crew— Figure 9 illustrates a portion of the protocol in which the crew implicitly acknowledge the existence of plans, and the need for appropriate conditions to invoke a particular plan for a goal. The pilot flying and the pilot-not-flying are considering two plans to achieve the goal of staying on the published course: Hand flying and AP Course Capture. The pilot flying indicates disapproval of the AP Course Capture plan until a certain altitude and DME has been achieved.

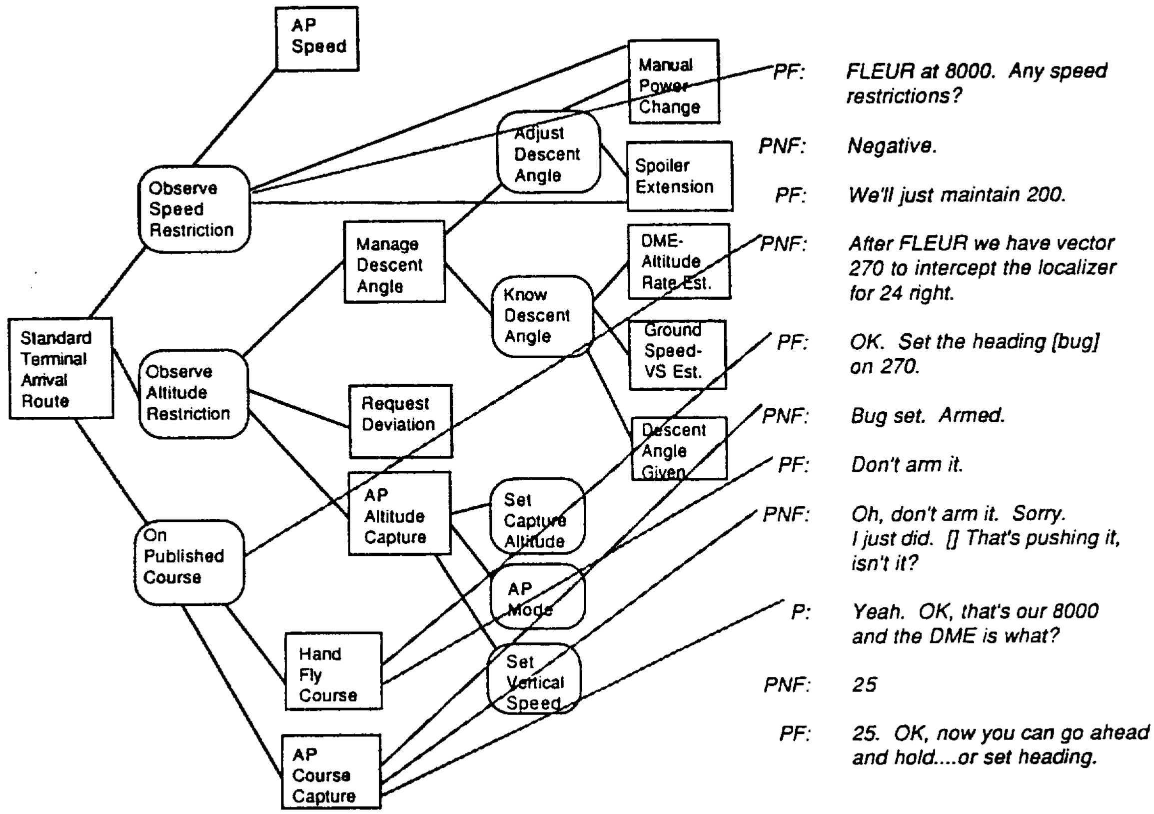


Figure 9. Crew discussion.

The participation of multiple agents in plans— Figure 10 illustrates the manner in which shared knowledge of a plan aids in the coordination of performance between multiple agents. By referencing the domain specific plan of using a Published Missed Approach, the pilot flying divides up the activities for that plan between himself and the pilot not flying.

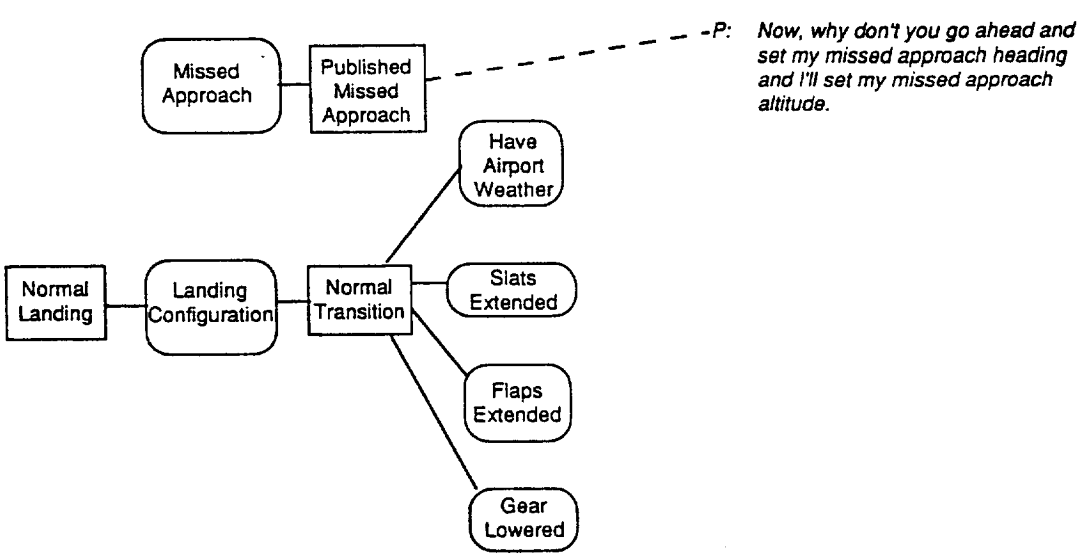


Figure 10. Participation of multiple agents.

Requirements for plan granularity Certain aspects of the initial plan and goal graph had to be modified in light of the protocol data. In analyzing the discussion in illustrated Figure 11a, it was clear that something was missing in the plan and goal graph. The initial graph implicitly subsumed the goal of observing the speed restriction as part of observing the altitude restriction. This resulted in the lack of an obvious link for the pilot's comment regarding the relationship between the Spoilers and the speed. In response to this portion of the protocol, the plan and goal graph was expanded to include the goal to Observe Speed Restriction, and an alternative plan for that goal was added, AP Speed.

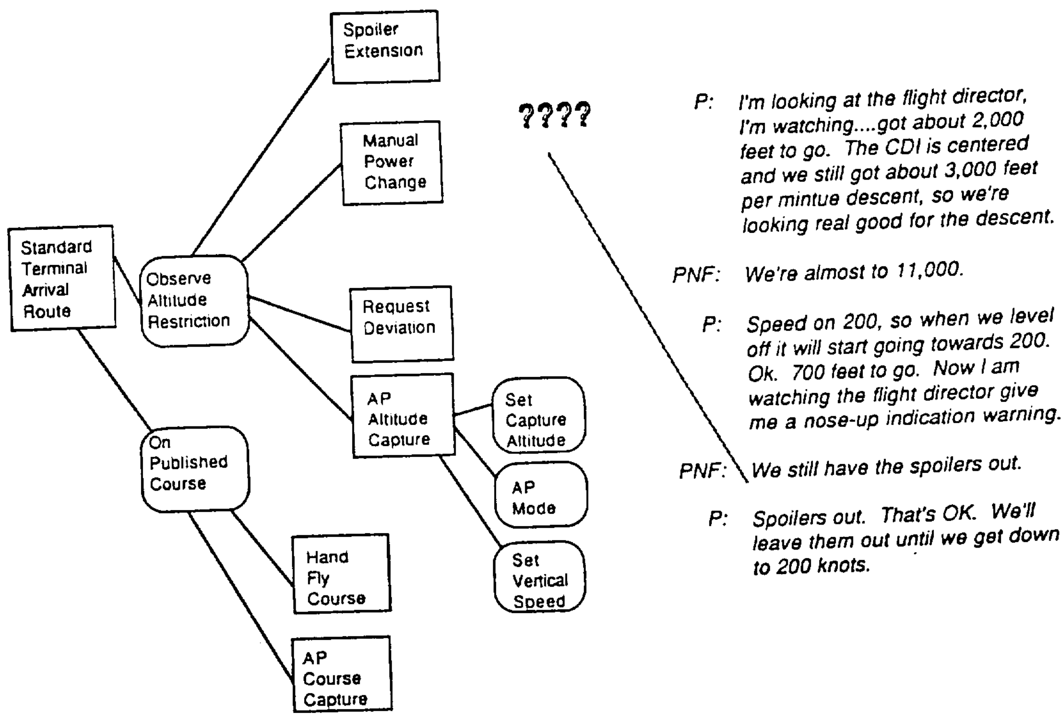


Figure 11a. Initial plan granularity.

We note that the granularity of plans will influence the rate at which potentially disruptive display changes occur, so there is some advantage to keeping plans at a high level of abstraction. However, overly abstract plans could cause information to persist after its utility has passed. These issues are best resolved with specific experimental results, and an information management policy that balances the tradeoffs of display change rate accordingly.

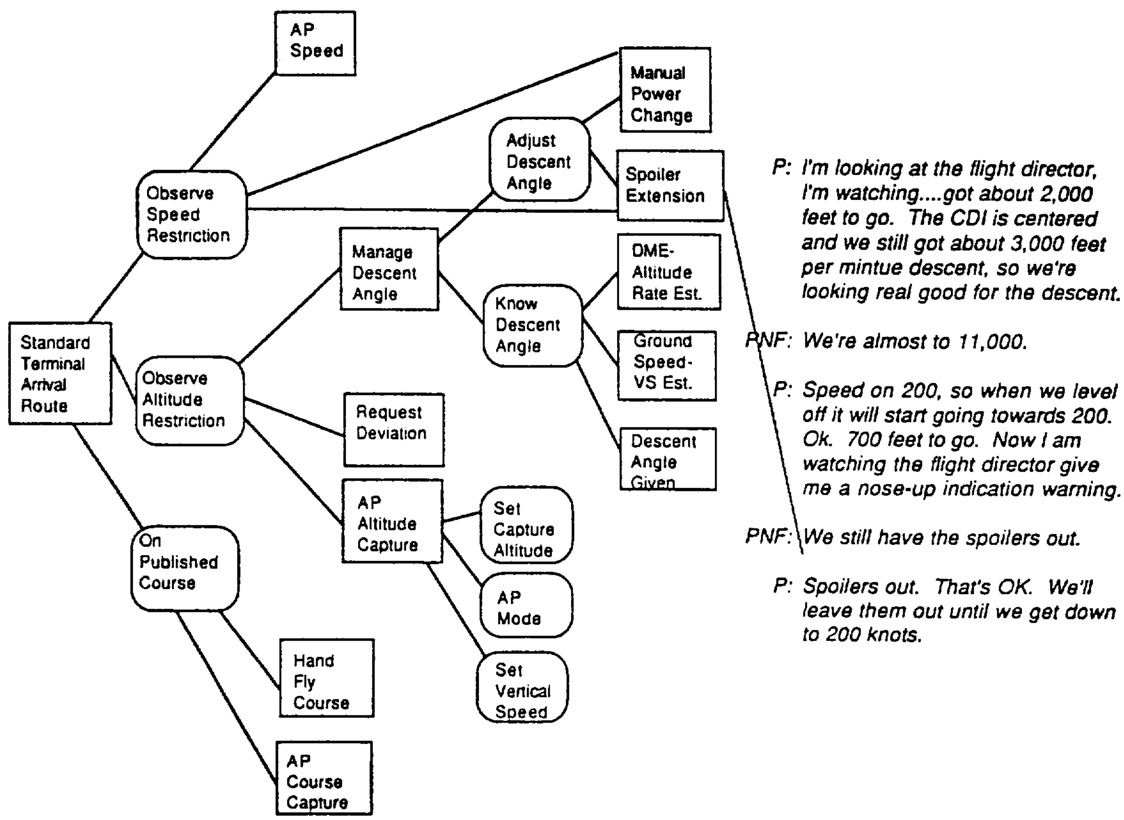


Figure 11b. Revised plan granularity.

4.2.4 Comments on plan and goal graph analysis

To the extent that *alternative plans exist for the same goal*, and to the extent that these *alternatives have different information requirements*, the plan-based information presentation method was supported by these analyses. The manner in which the protocol data were obtained have some influence on the proposed graph. There are no doubt artifacts associated with the experiment, the simulator, the reliability of information in the current crew station, and the currently availably mechanisms for accessing information in the present airspace system.

Because information reliability is a persistent problem at least currently, the plan and goal graph should be modified to contain an abstract goal for verifying information. In addition, some top level plans are probably missing, and the activities at glide slope intercept should be expanded.

After the basic goals and plans are in place, an important next step is determining the information requirements at both interior and leaf not plans.

4.3 Jumpseat Observations

In addition to this review of existing data, we are also collecting our own observations of the commercial aviation environment by riding jumpseat on USAir. These observations suggest that pilots have difficulty managing information only when the situation departs in some way from the ideal stereotype, including for example, stress associated with bad weather, an unfamiliar airport, a crowded environment, unanticipated deviations, and new equipment. Under these circumstances the consequences of inadequately presented information become potentially operationally significant.[4]

4.4 ASRS Database Search

Finally, as part of our efforts to confirm the appropriateness of a plan-based approach to determining information requirements, we have recently initiated a search of the ASRS database. We have received over 1,000 relevant reports, and analysis will proceed on these during the second half of the year.

4.5 Extend Explanation of Plan-Information Relationship to Information-Presentation Element Relationship

We have noted that presentation elements must be characterized in terms of the same parameters as information elements, so that appropriate presentation elements can be selected for a given task. Our previous work addressed the relationship between plans and parameterized information elements, but not the relationship between parameterized presentation elements and human information processing. We are making use of the existing literature to guide the development of computational rules to represent this relationship. Our ongoing review of the literature covers Human Factors, Psychology, Computer Science, Engineering and Decision Sciences. A partial list of the sources under consideration is provided in Table 1.

[4]This point is discussed further below in the subsection on dependent measures.

Table 1
Partial List of Literature Review Sources

ACM - Association of Computer Machinery	IEEE Transactions of Systems, Man, and Cybernetics
Aerospace America	Information and Management
Applied Ergonomics	International Journal of Man-Machine Studies
British Journal of Psychology	Journal of Experimental Psychology
Cognitive Science	Naecon Proceedings
Cognition and Emotion	Organizational Behavior and Human Decision Processes
Decision Support Systems	Proceedings of CHI
Ecological Psychology	Proceedings of the Human Factors Society
Human Computer Interaction	Scandanavian Journal of Psychology
Human-Computer Interaction and Complex Systems	Spatial Vision
Human Factors	The Quarterly Journal of Experimental Psychology
Human Factors Handbook	Tasks, Errors and Mental Models (Book)
Human Resources Research Organization	Visible Language
IEEE Transactions on Software Engineering	

An on-line database of this literature is being developed with Paradox software. Forty articles have been entered thus far, addressing the following topics:

- The relationship between plans and information requirements.
- The relationship between interpretation time and bandwidth.
- The relationship between interpretation time and resolution.
- The task conditions requiring specific values of scope.
- Interactions between presentation elements.
- Pilot scanning behavior.
- Evaluation techniques for information management.

Some of the findings are described below.

4.5.1 The relationship between plans and information requirements

The relationship between plans and information requirements is often addressed as a secondary issue in research papers on other topics. In their study of instructions for operating devices, Kieras and Bovair (1984) concluded that useful information supports the inference of steps for operating the device. Roth, Woods and Gallagher (1986) studied the behavior of process control operators. They concluded that experts anticipate the course of system responses, and develop control strategies to manipulate process dynamics to their advantage, test system dynamics and obtain data not otherwise available.

4.5.2 The relationship between interpretation time and bandwidth

In a substantial study of eye movements in pilot performance, Harris and Spady (1985) reached a number of conclusions regarding the amount of time that data are examined and interpreted. These conclusions address distinctions between monitoring a state and controlling a state, and call attention to the role of flight mode in the examination and interpretation of data. Cheal, Lyon and Hubbard (1991) have demonstrated the additional interpretation effort required by specific features of display elements, such as line arrangements, line orientation and the need to disengage attention.

4.5.3 The relationship between interpretation time and resolution

Yntema (Yntema, 1963; Yntema and Mueser, 1960; 1962) conducted studies of memory span performance that are widely acknowledged to be well ahead of their time. His primary concern was the tradeoff between number of variables and the number of states, when designing information displays. The conclusion from this work is that fewer variables with many states is preferable to many variables with fewer states. This conclusion is relevant to both resolution and scope decisions.

Keinan, Friedland and Arad (1991) suggest that subjects under stress naturally sort information into fewer, larger groups.

4.5.4 The task conditions requiring specific values of scope

Hanson, Payne, Shively and Kantowitz (1981) and Spenkelink (1990) both note the disadvantage of digital displays for recovering trend information. In our analysis of information requirements, we would make a distinction between state information and trend information. Some tasks require both kinds of information about a variable, and some tasks require only one or the other.

4.5.5 Interactions between presentation elements

Wrolstad (1976) and Wendt (1982) provide general discussions of the advantages of pictorial and typographic displays. Of course, the important issue is the interaction between the various display elements, and the task in question (Byblow, 1990; Morris & Jones, 1990; Sorkin and Woods, 1985). The significance of this issue for information management concerns the process of assigning a presentation element for an information source. The existing presentation element evaluation algorithm does not include the interaction of the candidate presentation element with other presentation elements.

4.5.6 Pilot scanning behavior

Harris *et al.* noted the situation dependent nature of instrument scanning. This supports the basic idea of information management. However, they also note that scanning is centered around a home base. Marcus (1974) suggests that standard display entry points facilitate processing time. The possibility of ritualized scanning behavior is a potential concern for information management, because the changes in displays may interrupt a highly automatic skill.

4.5.7 Evaluation techniques for information management

Lundberg (1990) suggests that the evaluation of expert systems and information retrieval systems are related problems. Completeness and precision are the important dimensions, and the amount of search activity is the suggested dependent measure. Purcell and Coury (1991) caution that the evaluation of alternative displays is sensitive to the order in which they are learned. This has implications for both specific experimental designs, and the carryover of pilot experience with traditional displays.

4.6 Experimental Work: Develop Predictive Methods

4.6.1 Experimental design

Based on the existing plan-and-goal graph, we have selected the area of observing speed restrictions while executing a Standard Terminal Arrival Route for our initial experimental work. The purpose of this experimental work is to test specific hypotheses of plans and associated information.

Design and hypotheses— We are currently constructing alternative versions of displays for three suitable plans for observing speed restrictions. Each display will be tailored for a particular plan, by manipulating the contents of the information as well as the parameters governing its presentation and management. A supporting computational system will substantiate the appropriateness of each display for its own plan, as well as the relative inappropriateness of a display for a sibling plan. The hypotheses associated with this design are summarized in Figure 12. We expect to see a relative facilitation for the display used in the context of its intended plan, and reduction in performance quality when less appropriate displays are used. We have developed a Three-by-Three design so that we could examine the performance impact of different amounts of departure from the display defined by the methods.

Display Tailoring

Plan	Manual Control	Use Autopilot	Use Spoilers
Manual Control	+	0	0
Use Autopilot	0	+	0
Use Spoilers	0	0	+

\+ Indicates conditions in which the plan and display are aligned
0 Indicates conditions in which the plan and the display are not aligned

Figure 12. Alternative displays crossed with alternative plans.

Dependent measures— We have a sufficiently precise hypothesis to permit the use of a quantitative dependent measure, and have chosen response time, with a secondary task imposed primarily to mitigate ceiling effects. Response time correlates with error in general, and in particular in this domain, as illustrated by the analysis in Figure 13

Best Case		Typical Case	
Visual Symbol Access	~10 msec	Visual Symbol Access x 10	~100 msec
Deliberate Operation	~10 msec	Double Composed Deliberate Operation	~10,000 msec
Lag after Control Action	~2500 msec	Lag after Control Action	~2,500 msec
Completion of Contol Action	~1000 msec	Completion of Control Action	~1,000 msec
	3,520 msec		13, 600 msec

(500 mph = 730 ft/sec)
Minimum distance to react = Total combined speed * Total Time
= 1460 ft/sec * 3.53 sec ~ 1 mile
Maximum distance to react = 1460 ft/sec * 13.6 sec ~ 3.5 mile

Figure 13. Potential operational significance of delayed response time.

4.6.2 Conduct experiment

Procedure—The experiment will be conducted in a fixed-based simulation environment, at SUNY Buffalo using HOOPS graphical programming language running on a SUN Sparc2 through SunView. Pilot responses will be video and audio-taped, and pilot inputs into the simulation environment will capture any additional features of the context.

Subjects—We have requested the assistance of USAir, the Air National Guard, and ALPA in locating line pilots for use as subjects. Approximately 9 subjects will be required, crossing three plans with three displays. Each subject will participate in an experimental session of not longer than 2 hours.

Expected Results—We expect the experiment to demonstrate facilitated task performance based on the use of method-based displays. Moreover, performance with alternative displays should degrade in proportion to their departure from the method-based. This will illustrate that plan-based information management has the potential to enhance performance.

5 Outcomes & Anticipated Results

5.1 Multi-year

We expect significant practical and theoretical contributions from the proposed line of research. One practical contribution is the development of a partially automated method for use by industry in choosing an information management policy, selecting information requirements attributes and implementing interfaces. We expect to obtain some quantitative estimates of performance advantages associated with intelligent information management, and principled selection of information grain size and display parameters.

The proposed research also promises to integrate basic perceptual and cognitive theory with the threads of applied psychology and human factors being incorporated into information management and interface design. Moreover, the additional cognitive theory developed for this applied problem in human factors is specifically intended to influence cognitive science in the same way that applied problems in education have influenced the development of the field. Specifically, we anticipate a theoretical contribution to the representation of models of human knowledge for tasks in a manner that links cognitive and perceptual processes with a real world task environment.

6 Bibliography

Abbott, T.S. (1989). Task oriented display design: Concept and example. Unpublished Master's Thesis, Department of Computer Science, College of William and Mary, Virginia.

Anderson, J.R. (1983). *The architecture of cognition.* Cambridge, MA: Harvard University Press.

Bainbridge, L. (1974). Analysis of verbal protocols from a process control task. In E. Edwards & R.P. Lees (Eds.), *The human operator in process control,* London: Taylor & Francis.

Bloomfield, J.L., Shalin, V. L., & Corwin, W.H. (1990). Knowledge sensitive task manipulation: Acquiring knowledge from pilots flying a motion-based flight simulator. Paper presented at the 1990 meeting of the Midwestern Human Factors Society, Dayton, OH, and the 1991 Aviation Psychology Meeting, Columbus Ohio.

Bransford, J.D. & Johnson, M.K. (1973). Consideration of some problems in comprehension. In W.G. Chase (Ed.), *Visual information processing.* New York: Academic Press.

Briars, D.J. & Larkin, J.H. (1984). An integrated model of skill in solving elementary word problems. *Cognition & Instruction, 1* 245-296.

Byblow, W.D. (1990). Effects of redundancy in the comparison of speech and pictorial displays in the cockpit environment. *Applied Ergonomics,* 21(2), 121-128.

Carroll, J.M. (Ed.)(1991). *Designing Interaction.* Cambridge University Press: Cambridge.

Carroll, J.M., Kellogg, W.A., & Rosson, M.B. (1991). The task-artifact cycle. In J. Carroll (Ed.) *Designing Interaction.* Cambridge University Press: Cambridge.

Chase, W.G. & Simon, H. (1973). Perception in chess. *Cognitive Psychology,* 4, 55-81.

Cheal, M., Lyon, D.R. & Hubbard, D.C. (1991). Does attention have different effects on line orientation and line arrangement discrimination? *Quarterly Journal of Experimental Psychology,* 43(4), 825-827.

Chi, M.T.H., Feltovich, P. & Glaser,. R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science, 5,* 121-152.

Edwards, G.R. & Geddes, N.D. (1991). Deriving a domain-independent architecture for Associate Systems from essential elements of associate behavior. *Associate Technology: Opportunities and challenges,* P.E. Lehner (Ed.), Fairfax, VA: George Mason University, June, 17-29.

Ericcson, K.A. & Simon, H.A. (1986). Verbal reports as data. *Psychological Review, 87,* 215-251.

Forbus, K.D. (1990). The qualitative process engine. In D.S. Weld & J. deKleer (Eds.) *Readings in Qualitative Reasoning about Physical Systems,* Morgan Kaufmann.

Geddes, N.D. & Hammer, J.M. (1991). Automatic display mapnagement using dynamic plans and events. In *Proceedings of the Sixth Symposium on Aviation Psychology*, Columbus, OH, April 30 - May 3.

Geddes, N. D. (1990). Test and evaluation of the Pilot's Associate. Workshop on test and evaluation of expert systems in airborne tactical applications. Naval Air Test Center, Patuxent River, Md.

Geddes, N. D. & Hoffman, M. A. (1990). Supervising unmanned roving vehicles through an intelligent interface. *Proceedings of the 1990 Space Operations and Robotics Conference.* Albuquerque, NM.

Geddes, N.D. (1989). Understanding Human Operators' Intentions in Complex Systems. Unpublished Doctoral dissertation, Georgia Institute of Technology, Atlanta, GA.

Gibson, J.J. (1979). *The ecological approach to visual perception.* Boston: Houghton-Mifflin.

Greeno, J.G. (1976a). Cognitive objectives of instruction: Theory of knowledge for solving problems and answering questions. In D. Klahr (Ed.), *Cognition and instruction.* Hillsdale, N.J.: Erlbaum.

Greeno, J.G. (1976b). Indefinite goals in well-structured problems. *Psychological Review, 83*, 479-491.

Greeno, J.G. (1978b). A study of problem solving. In R. Glaser (Ed.), *Advances in instructional psychology (Vol. 1).* Hillsdale, N.J.: Erlbaum.

Greeno, J.G. (1980). Psychology of learning, 1960-1980: One participant's observations. Technical Report No. 5. Office of Naval Research, Contract No. N00014-78-C-022.

Greeno, J.G. (1982). Forms of understanding in mathematical problem solving. In S. Paris, G.M. Olson, & H.W. Stevenson (Eds.), *Learning and motivation in the classroom.* Hillsdale, N.J.: Erlbaum.

Greeno, J.G., (1983). Conceptual entities. In D. Gentner, & A. Stevens (Eds.), *Mental Models*, Hillsdale, N.J.: Erlbaum.

Greeno, J.G., Brown, J.S., Foss, C., Shalin, V.L., Bee, N.V., Lewis, M., & Vitolo, T.M. (1986). Cognitive principles of problem solving and instruction. Report 41, Berkeley Cognitive Science Report Series.

Greeno, J.G., Magone, M.E., & Chaiklin, S. (1979). Theory of constructions and set in problem solving. *Memory and Cognition, 7*, 445-461.

Greeno, J.G., Riley, M.S., & Gelman, R. (1984). Conceptual competence and young children's counting. *Cognitive Psychology, 16*, 94-143.

Hanson, R.H., Payne, D.G., Shively, R.J. & Kntowitz, B.H. (1981). Process control simulation research in monitoring analog and digital displays. *Proceedings of the 25th Annual Meeting of the Human Factors Society,* 154-158.

Harris, R.L. & Spady, A.A. (1985). Visual scanning behavior. In *Proceedings of NAECON '85,* 1032-1039.

Howard, C.W., Hammer, J.M., & Geddes, N.D. (1988). Information Management in a Pilot's Associate. *Proceedings of the 1988 Aerospace Applications of Artificial Intelligence Conference*, 1, 339-349.

Hutchins, E. (in press). Learning to navigate. In S. Chaiklin and J. Lave (Eds.) *Understanding practice.* New York: Cambridge University Press.

Jordan, N. (1963). Allocation of functions between man and machine in automated systems. *Journal of Applied Psychology, 47.*

Kantowitz, B.H. (1989). The role of human information processing models in system development. *Proceedings of the Human Factors Society 33rd Annual Meeting,* Santa Monica, CA: The Human Factors Society.

Keinan, G., Friedland, N., & Arad, L. (1991). Chunking and integration: Effects of stress on the structuring of information. *Cognition and Emotion,* 5(2), 133-145.

Kieras, D.E. & Bovair, S. (1984). The role of a mental model in learning to operate a device. *Cognitive Science,* 255-273.

Kintsch, W. & Greeno, J.G. (1985). Understanding and solving word arithmetic problems. *Psychological Review, 92*, 109-129.

Kosslyn, S.M. (1985). Graphics and human information processing: A review of five books. *Journal of the American Statistical Association, 80*, 499-512.

Kotovsky, K., Hayes, J.R., & Simon, H.A. (1985). Why are some problems hard? Evidence from the Tower of Hanoi. *Cognitive Psychology, 17,* 248-294.

Kotovsky, K. & Simon, H.A. (1990). What makes some problems really hard: Explorations in the problem space of difficulty. *Cognitive Psychology, 22* 143-183.

Larkin, J.H. (1982). The role of problem representation in physics. In D. Gentner & A. Collins (Eds.), *Mental models.* Hillsdale: N.J.: Erlbaum.

Lave, J. (1988). *Cognition in practice: Mind, mathematics and culture in everyday life.* Cambridge: Cambridge University Press.

Lesgold, A., Rubinson, H., Feltovich, P., Glaser, R., Klopfer, D., & Wang, Y. (1988). Expertise in a complex skill: Diagnosing X-ray pictures. In M.T.H. Chi, R. Glaser, & M.J. Farr (Eds.), *The nature of expertise.* Hillsdale, NJ: Erlbaum.

Lundberg, B.G. (1990). On the evaluation of heuristic information systems. *Decision Support Systems,* 6, 253-259.

Marcus, A. (1974). An introduction to the visual syntax of concrete poetry. *Visible Language,* 8(4), 333-360.

McDermott, J. & Larkin, J.H. (1978). Re-representing textbook physics problems. In *Proceedings of the Second National Conference, Canadian Society for Computational Studies of Intelligence.* Toronto: Canada: University of Toronto.

Meister, D. (1991). The epistemological basis of human factors research and practice. *Proceedings of the Human Factors Society 33rd Annual Meeting,* Santa Monica, CA: The Human Factors Society, 1275-1279.

Miller, G.A., Galanter, E.H., & Pribram, K.H. (1960). *Plans and the structure of behavior.* New York: Holt, Rinehart & Winston.

Minsky, M. (1975). A framework for representing knowledge. In P. Winston (Ed.) *The psychology of computer vision.* New York: McGraw-Hill.

Morris,N. & Jones, D.M. (1990). Memory updating in working memory: The role of the central executive. *British Journal of Psychology,* 81, 111-121.

Newell, A. (1991). *Unified theories of cognition,* Harvard University Press, Cambridge.

Newell, A. (1982). The knowledge level. *Artificial Intelligence, 18,* 87-127.

Newell, A. (1980). Reasoning, problem-solving, and decision processes: The problem space as a fundamental category. In R. Nickerson, (Ed.), *Attention and performance VIII.* Hillsdale, N.J.: Erlbaum.

Newell, A., & Simon, H. (1972). *Human problem solving.* Englwood Cliffs, N.J.: Prentice-Hall.

Nisbett, R.T. & Wilson, T.D. (1977). Telling more than we can know: Verbal reports on mental processes. *Psychological Review, 84(3),* 231-259.

Norman, D.A. (1991). Cognitive artifacts. In J. Carroll (Ed.) *Designing Interaction.* Cambridge University Press: Cambridge.

Norman, D.A. & Draper, S.W. (Eds.) (1986). *User centered system design: New perspectives in human-computer interaction.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Paige, J.M., & Simon, H.A. (1966). Cognitive processes in solving algebra word problems. In B. Kleinmuntz (Ed.), *Problem solving.* New York: John Wiley & Sons.

Purcell, J.A. & Coury, B.G. (1990). The impact of alternating between integral and separable displays in a multidimensional decision-making task. In *Proceedings of the 35th Annual Meeting of the Human Factors Society,* 1579-1583.

Roth, E.M., Woods, D.D. & Gallagher, J.M. (1986). Analysis of expertise in a dynamic control task. *Proceedings of the Human Factors Society 30th Annual Meeting,* 179-181.

Rouse, W.B., Geddes, N.D. & Hammer, J.M. (1990). Computer-aided fighter pilots. *IEEE Spectrum March*, 38-41.

Rouse, W.B., Geddes, N.D., & Curry, R.E. (1987). An architecture for intelligent interfaces: Outline of an approach to supporting operators of complex systems. *Human-Computer Interaction*, 3, 87-122.

Rouse, W.B. & Morris, N. (1986). On looking into the black box: Prospects and limits in the search for mental models. *Psychological Bulletin, 100(3),* 349-363.

Sacerdoti, E.D. (1977). *A structure for plans and behavior.* New York: Elsevier-North Holland.

Sanders, M.S. & McCormick, E.J. (1987). *Human factors in engineering & design.*, New York: McGraw Hill.

Schneider, W. (1985). Training high-performance skills: Fallacies and guidelines. *Human Factors, 27*, 285-300.

Scribner, S. (1984). Studying working intelligence. In B. Rogoff & J. Lave (Eds.) *Everyday cognition: Its development in social context.* Cambridge, MA: Harvard University Press.

Sewell, D.R. & Geddes, N.D (1990). A plan and goal based method for computer-human system design. *Human Computer Interaction: INTERACT 90*, New York: North- Holland. 283-288.

Sewell, D.R., Geddes, N.D., & Rouse, W.B. (1987). Initial evaluation of an intelligent interface for operators of complex systems. In G. Salvendy (Eds), *Cognitive engineering in the design of human-computer interaction and expert systems* (551-558). New York: Elsevier.

Shalin, V. L., Geddes, N. D., Hoshstrasser, B. D., Miller, C.A., Levi, K. R., and Persbacher, D. L. (1990). Towards a theory of pilot information requirements during plan development and execution. *Proceedings of CERT 90. Toulouse, France.*

Shalin, V. L., Miller, C. A., Geddes, N. D., Hoshstrasser, B. D., Persbacher, D. L. and Levi, K. R. (1990). Automated acquisition of information requirements for an intelligent display. *Proceedings of the 1990 Space Operations and Robotics Conference.* Albuquerque, NM.

Shalin, V.L. (1982). Solving problems with supplied diagrams. Paper presented at the 54th Annual Meeting of the Midwestern Psychological Association, Minneapolis, MN.

Sheridan, T.B. (1991a). Automation, authority and angst. *Proceedings of the 35th Annual Meeting of the Human Factors Society,* Human Factors Society, Santa Monica, 2-6.

Sheridan, T.B. (1991b). Methodology for tackling the bigger problems. *Human Factors Society Bulletin, 34(12),* 2-4.

Sheridan, T.B. (1991c). New realities of human factors. *Human Factors Society Bulletin, 34(2),* 1-3.

Simon, H.A. (1969). *The sciences of the artificial.* Compton Lectures, Cambridge, MA: MIT Press.

Simon, H.A. (1979). Information-processing theory of human problem solving. In W. Estes (Ed.), *Handbook of learning and cognitive processes*, (Vol. 5). Hillsdale, NJ: Erlbaum.

Simkin, D. & Hastie, R. (1987). An information processing analysis of graph perception. *Journal of the American Statistical Association, 82(398)* 454-465.

Sorkin, R.D. & Woods, D.D. (1985). Systems with human monitors: A signal detection analysis. *Human Computer Interaction,* 1, 49-75.

Spenkelink, G.P.J. (1990). Aiding the operator's anticipatory behavior: The design of process state information. *Applied Ergonomics,* 21(3), 199-206.

Spoehr, K.T. & Lehmkuhle, S.W. (1982). *Visual information processsing.* W.H. Freeman: New York.

Springer, K. (1990). In defense of theories. *Cognition, 35,* 293-298.

Smith, S. & Mosier, J. (1989). *Guidelines for designing user interface software,* Santa Monica: Human Factors Society.

Suchman, L. (1987). *Plans and situated actions: The problem of human-machine communication.* Cambridge: Cambridge University Press.

Vicente, K.J. (1990). A few implications of an ecological approach to human factors. *Bulletin of the Human Factors Society, 33(11),* 1-4.

Vicente, K.J. & Rasmussen, J. (1990). The ecology of human-machine systems II: Mediating "direct perception" in complex work domains. *Ecological Psychology, 2* 207-250.

Webb, B. W., Geddes, N. D. and Neste, L. O. (1989). Information management with a hierarchical display generator. *Proceedings of the National Computer Graphics Association,* Washington, D.C.

Wendt, D. (1982). Improving the legibility of textbooks: Effects of wording and typographic design. *Visible Language,* 16(1), 88-93.

Wenger, E. (1987). *Artificial intelligence and tutoring systems.* Los Altos, CA: Morgan Kaufmann.

Wertheimer, M. (1945/1959). *Productive thinking.* (enlarged edition). New York: Harper.

Winograd, T. & Flores, F. (1986). *Understanding computers and cognition: A new foundation for design.* Norwood, NJ: Ablex Publishing Corporation.

Wrolstad, M.E. (1976). A manifesto for visible language. *Visible Language,* 10(1), 5-40.

Yntema, D.B. (1963). Keeping track of several things at once. *Human Factors,* 2, 7-17.

Yntema, D.B. & Mueser, G.E. (1960). Remembering the present states of a number of variables. *Journal of Experimental Psychology,* 60, 18-22.

Yntema, D.B. & Mueser, G.E. (1962). Keeping track of variables that have few or many states. *Journal of Experimental Psychology,* 63(4), 391-395.

A PA and LSIR Background

LSIR—the Learning System for Information Requirements was sponsored by Wright Research and Development Center, and conducted in the context of the Intelligent Pilot Vehicle Interface (PVI) from the Pilot's Associate (PA) program, developed by Search Technology and Lockheed under the sponsorship of DARPA and the Air Force (Rouse, Geddes & Hammer, 1990).

A.1 The Pilot's Associate PVI

The PVI is an intelligent subsystem that links the Pilot's Associate system and the pilot. It determines the content, modality, and format of messages, determines pilot intent, manages the display resources consistent with pilot intent, and transfers his intentions and instructions to the aircraft systems (Rouse, Geddes & Curry, 1987).

The inputs to display selection are estimates of pilot intent, direct input from the switches and touch panels in the cockpit, and knowledge of information requirements associated with certain plans (Howard, Hammer & Geddes, 1988). The knowledge is referred to as the *information requirements* (IR) knowledge structure. The IR knowledge structure must be associated with a plan name and consists of a list of sublists describing *information elements*. An information element corresponds directly or indirectly to a dimension of the data environment in which the PA operates.

Display generation proceeds by first matching the information requirements (IR) knowledge structure to the available display elements capable of illustrating each of the parameterized information elements on the list of information requirements (Webb, Geddes & Neste, 1989). Display space is managed by mapping display elements onto predefined units of space, starting from the center of the display, and moving outwards, according to the importance value of the information.

A.2 The LSIR Process

For the PA program, the IR knowledge structure associated with plans was defined through standard knowledge acquisition and knowledge engineering activities. On the LSIR program, the IR knowledge structure is being *computed* from a description of the plan and a set of rules explicitly relating plan features to information requirements and their parameters. The process of determining information requirements for a plan proceeds as follows:

- Begin with a coded statement of a plan, such as the one shown below.

- Using this statement, and event-recognition rules, determine the presence of key events in the plan. The current rule set is capable of recognizing the existence of an RWR-use event, and two Course events: precision-fixed-horizontal-course and gross-fixed-horizontal-course. Also in place is much of the domain theory to recognize Long- and Short-range-radar-use events and the fixed vs. dynamic, horizontal vs. vertical vs. speed, and precision vs. nominal vs. gross distinctions in course events. Defining the set of useful events is a continuing research problem. *Major changes to the goals of flying an airplane (e.g., hovering) would impact this portion of the methods for determining information requirements.*

Events related to selecting, specializing and transitioning the plan:
- Enemy in weapon range
- Enemy radar search
- Enemy radar track
- Potential enemy-radar-guided weapon launch

Events related to executing the plan:
- Fixed-precision course
- Fixed-gross course
- Short-range RWR use

Figure A1. A representation of the plan for Doppler Notch in terms of events.

- Assert a list of Information Sources with Task Dependent values which are called for by each recognized event. The proper grain size and level of analysis for an information source is yet to be determined. The smallest possible grain size is the raw data reported by specific aircraft systems. *Thus, much of the impact of different aircraft systems may be localized to this portion of the methods for determining information requirements.*

  Task dependent values represent primitive properties of the information that are sensitive to the context of the task. An examples of a task dependent attributes of information is *Task Significant Difference.* Task Significant Difference is dependent upon the amount of error that a particular method executed for a particular purpose can tolerate. Task significant difference determines the appropriate aggregation for a display of a continuous quantitative scale into qualitative states that elicit the same operator response within a state.

- Obtain Task-Independent attribute values for each of the ISs included by an event. For example, the *possible* Range of an information element (e.g., 0 - 50,000 foot range of possible altitudes) is independent of the activity or method.

- Use the Task-Dependent and Task-Independent values associated with each IS in each event as inputs to a *combination calculus* and derive, as outputs, Scope, Resolution and Bandwidth values for each source of information in that Event. The use of these particular output values is constrained by the information management system we are using. *If the information management system were to change, we might be required to output values for other dimensions.*

  Figure 4 in section 2 illustrates the influence of task dependent and task independent attributes on the calculation of scope, resolution, and bandwidth values. The concern for *human perception and cognition is particularly prominent in this portion of the rule-base.* For example, the fastest possible update rate is fixed at the fastest possible rate at which a human can identify and interpret data, independent of the update rate of the raw sensors. The pilot's ability to predict the value of an information source constitutes a significant portion of the calculation, and is based in large part on signal detection theory.

- Aggregate the parameter values for the same IS resulting from multiple concurrent events within a plan, so that each IS is left with only one scope, resolution and bandwidth value. Aggregation is currently done by simply taking the largest values.

	Scope	Resolution	Bandwidth
Flight-path-vertical angle	4	10	6
Flight-path-horizontal angle	7	9	8
G-loading	5	6	6
Heading	6	10	7
Indicated Airspeed	4	9	7
Thrust	4	5	5
Track-Azimuth	7	10	9
Track-Bearing	6	10	7
Track-ID	1	8	2
Track-Range	8	9	9
Angle of Attack	6	8	6
Roll	6	9	8
EW-mode	3	2	4
EW-status	3	1	3
Track-class	4	5	3
Track-radar-mode	7	3	8
Track-type	5	7	5
TSD-range-scale	3	1	3
Track-altitude	6	6	6
Track-heading	8	8	9
Track-range-rate	8	9	9
Track-speed	7	7	8

Figure A2. An IR knowledge structure for the Doppler Notch Maneuver.

A.3 Evaluation of Plan-based Information Management and Methods

The idea of plan-based information requirements and the associated rule set relating plans to information is fairly new, and its evaluation has only just begun. Some preliminary evaluation indicates that the parameters used in the calculus is could be reduced with no impact to the final calculations.

However, without the aid of LSIR, human knowledge engineers are not consistent with each other. In some cases, human subjects provide very modest indications that some of the LSIR parameters may be governing their thinking. The general conclusion is that the task of determining parameter values for an information management system is too complex for human knowledge engineers. Other than these results, LSIR has not been subjected to experimental testing with pilots, its performance limitations have yet to be exposed.

Two kinds of limitations are of concern: Theoretical and practical. Theoretical limitations have to do with the feasibility of *methodically* determining correct, complete and delimited information requirements, given infinite effort. Examples of potential theoretical limitations are: excessive, tailored assumptions about independent, concurrent context that must be acknowledged in constructing the information requirements list, or frame-problem issues in controlling the growth of potentially related information. Practical limitations have to do with the costs and benefits of the plan-based approach relative to standard methods. An example of a potential practical limitation is the depth and detail of plan specification required to identify only minor changes with respect to the information requirements identified using a situation-based approach. Another example of a practical limitation is the extent to which feedback from users can be gracefully accomodated and integrated into the methods for use in new situations. Practical limitations must be weighed differently than theoretical limitations, because the cost of the method may be balanced by an increase in capabilities. For example, a claim of the plan-based approach is that it generates changes in information requirements resulting from changes in equipment, as long as the functionality of the equipment is known. This capability is virtually absent from standard methods, which rely on operational experience in order to identify *post hoc* crew information requirements.

In addition to the need for empirical evidence to evaluate the plausibility of the approach, much of its refinement can only be resolved with data, such as the ideal granularity of the information elements, or the sufficiency of the parameter set.