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Questions: Assessing the structure of knowledge and the use of information in design problem-solving

McCracken, James Richard, Ph.D.

The Ohio State University, 1990

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Questions: Assessing the Structure of Knowledge and the Use of Information in Design Problem Solving

DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By

James Richard McCracken, M.Ed.

* * * *

The Ohio State University

1990

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College of Education
To My Family
ACKNOWLEDGEMENTS

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CHAPTER I
INTRODUCTION

Introduction

In this chapter, problems facing aerospace crew system design teams are reviewed. Problem statements are made and definitions are given. The limitations, delimitations and assumptions for the study are presented, and an overview of the dissertation is provided. This is an exploratory, descriptive study, seeking relationships, rather than predicting relationships to be found. As such, it has three general purposes (Katz, 1953): (1) to discover significant variables in the field situation.; (2) to discover relations among variables.; and (3) to lay the groundwork for later, more systematic and rigorous testing of hypotheses.

Nature of the Problem

There is a need for information system support for designers (Doppelt, 1987; Rouse & Boff, 1987) which has been well documented for 25 years (Meister & Farr, 1965,1967). There is a communication problem stemming from the multidisciplinary nature of design teams, also recognized for 25 years (Meister & Farr, 1965,1967; Boff, 1987). These two
problems are the focus of this dissertation. They give rise to two corollary problems.

First, how should the support system be structured, i.e., what should its components be? A growing number of builders of human-computer systems have noted the central role the user should play in the design of the system (Winograd and Flores, 1987; Gould & Lewis, 1985; Norman, 1936; Booth, 1989; Winograd, 1989). Most have some framework for the overall approach to system design, calling for user participation, though few address directly how to involve the user in the process. The human-computer interaction is the central issue at the interface between the resources of the system and the user because it mediates the transactions between the subject matter expert and the resources of the system in question. Support system success has been shown to be dependent on the structure inherent in the system matching structure inherent in the minds of users (Stabell, 1975). This success requires an assessment of the structure of knowledge held by the user population.

This requirement for an assessment of the structure of knowledge provides the second corollary problem: What is the appropriate set of methods to do the assessment, and how should they be employed in the setting in which the study takes place?
Cognitive Structure

The assessment of cognitive structure has implications for general system design and training (Hall et al., 1981). It is inherent in the knowledge acquisition process in the building of expert systems (Ericsson & Simon, 1984), and the identification of information requirements for information system design (MacMullin & Taylor, 1984). Assessing cognitive structure of users is at the heart of the design of human-machine cognitive systems (Woods, 1986; Norman, 1986). Graesser (1985) cited the need for a theory or model of question-asking and question-answering to provide direction to these kinds of functions. Others (Fleishman & Quaintance, 1984) have argued that "...past experience has provided few rigorous guidelines for determining the applicability of previously acquired data to new systems." and that "...both the principles of human-machine system design and the rules for their application are lacking." More generally, Ward (1983) called for research on development of descriptions and methods of studying written or spoken knowledge and knowledge-in-use, citing the difficulty of communicating across disciplines as one especially important focus of this need.

Need for the Study

This study's contribution is expected to be in the area of creating and refining a methodology to gain an understanding of designers' information seeking/problem-
solving behavior during the conceptual design process. In addition, it provides for communicating that understanding to system developers, and identifying areas which have the potential for support tool development. The purpose for which the data generated in this study is intended to be used is for the design of an information support system.

There currently is a lack of understanding of the question asking and information seeking behaviors within problem solving approach(es) that designers employ. This understanding is important to the following pursuits: (1) gaining insight into the conceptual design process by describing the process in a systematic way; (2) assessing the cognitive structures employed in complex problem-solving processes; and (3) creating tools to aid designers. Studies to develop understanding of the design process are needed in several areas.

Mostow (1985) cited three needs for improving the design process: (1) investigation of cognitive models of design; (2) development of techniques for acquiring design knowledge; and (3) the need to identify the goals of knowledge acquisition behaviors such as information seeking.

Rabins, in Goals and Priorities for Research in Engineering Design (1986) cited research needs for "intensive descriptive studies of successful designers and design behavior", and "intensive descriptive studies of design expertise". These descriptive studies should include
"exploration and evaluation of flexible methods of problem definition", "research on team design", and "study of the use of information in design".

The various concerns in these reports are addressed, either in whole or in part, by this dissertation. Specifically, these needs are addressed by: (1) gaining an understanding of the knowledge structures employed in the design process; (2) identifying points of effort for support system development; (3) evaluating a tool for enhancing communication within design teams; and (4) generating and testing methods for design knowledge acquisition which provides for an understanding of cognition of the design process.

Needs specification

Need for Design Support Systems

There is a need for information system support for designers (Doppolt, 1987; Rouse & Boff, 1987) which has been well documented for 25 years (Meister & Farr, 1965, 1967). Rouse & Boff (1987) also cite a need for developing knowledge based information processing methods to help designers keep track of relations among interdependent design issues. Rouse & Cody (1989) cite the need for matching information seeking behaviors to support system design. The identification of design issues by this research, and relations among problem-solving subtasks address this need.
Need to Enhance Design Team Communication

The difficulties in the access and use of information arise in particular when the information needed is of a cross-disciplinary nature (Boff, 1987). Boff addresses questions of information access, interpretation, and use with particular reference to the uses of human factors data in the design of Department of Defense systems. The problem was recognized by Meister & Farr (1965) and has persisted (Havelok, 1966; Meister & Sullivan, 1967; Meister & Farr, 1967; Lintz et al., 1971; Rouse, 1986; Sage, 1987; Aluissi, 1987).

Allen (1977) found that the frequency with which information seekers access sources varied approximately inversely with the square of the distance needed to travel to access it. There is an additional communication problem between knowledge acquisition personnel and the development team, difficult even when design teams are in close proximity to the users of the system, and which is exacerbated when the design teams perform their work in a location remote from the actual site of use of the design artifact (Bannon, 1986).

Need for Understanding the Cognition of the Design Process

As a result of the perceived need for information support and the difficulties in communication among design team
members and the previously mentioned need for the assessment of the knowledge structures employed by the users, there is a need for understanding the cognition of the design process. Knowledge of the cognitive processes of design has been the subject of several papers (Malhotra, Thomas, Carroll, 1980; Carroll, Thomas & Malhotra, 1979; Eastman, 1968). Design knowledge is discussed with respect to the building of knowledge based systems by Brown and Chandrasekaran (1989); Norman (1986,1988); Jones (1988); and Coyne et al. (1990). However, each of these investigations or reports were constrained to relatively small problem spaces, or were not in the context of crew systems, and do not provide guidance as to how to proceed with the present study.

Need for Methods for Design Knowledge Acquisition

A review of knowledge acquisition methodologies revealed no single technique that was adequate to the task of acquiring and representing the knowledge structures and information seeking behavior of designers during design problem solving (McCracken, 1987a; Boose, 1989). The review by Boose (1989) further showed that almost no knowledge acquisition techniques or tools dealt with the problem solution category of heuristic construction (Clancey, 1986) which is the problem-solving technique proposed for design synthesis.
Problem Statements

Problem 1 - What is the appropriate structure for an information support system for the target population?

Subproblem 1 Can question asking behaviors of the subject population be identified which provide insight as to requirements for support system development?

Subproblem 2 Can information seeking behaviors of the subject population be identified which provide insight as to requirements for support system development?

Subproblem 3 Can problem-solving behaviors of the subject population be identified which provide insight as to requirements for support system development?

Subproblem 4 Can points of effort be identified for development of the support system by detecting errors in design problem solving?

Subproblem 5 Do designers tend to use information sources which are closest to their place of work?
Problem 2 - Can techniques for supporting communication among the members of the target multidisciplinary design teams be identified?

Subproblem 1 Can the technique of question concept mapping enhance communication among members of the design team?

Problem 3 - Did the methods used provide an understanding of the cognition of the design problem-solving process?

Subproblem 1 Can a model of the question asking process be described from the data acquired by this study?

Subproblem 2 Does the type of question asked vary with the role on the design team?

Subproblem 3 Do different designers use different information seeking strategies?

Problem 4 - Can a set of methods to acquire knowledge to enable identification of solutions to the following subproblems be generated and implemented?

Subproblem 1 Can the methods identified acquire useful data on individual design problem solving?

Subproblem 2 Can the methods identified acquire useful data on group design problem solving?
Subproblem 3  Do the acquisition methods used for this study differ in their efficiency, measured in terms of rate of capture of questions?

Subproblem 4  Do the data acquisition methods differ in required processing time to generate data in terms of numbers of questions?

**Definitions**

aggregation - the generation of assemblies of objects with respect to some common thread, which may be function, form, goal or other common dimension.

concept map - a tool for knowledge acquisition that provides a concrete representation of the structure of knowledge of the subject population that allows for the negotiation of understanding between the expert and the knowledge engineer.

concept mapping - the process of knowledge acquisition that captures an expert's conceptual structure of a problem.

question concept mapping - concept mapping which, for reasons related to psychological theory, focuses on the questions asked during problem solving, using questions as the nodes of a network representation of the problem-solving process.

conceptual development - the set of subproblems within the design process which produce descriptions of the crew
system of varying type (graphic or text) and various levels of detail.

heuristic construction - the generation of design solutions through the aggregation of objects within the constraints of the problem space guided by heuristics of the domain (Clancey, 1986). The classification of problem solution strategy used here grows out of a scheme for classifying knowledge based application problems. The scheme, provided by Clancey (1986), divides knowledge based problems into analysis (interpretation) and synthesis (construction) problems, hence the term heuristic construction.

knowledge acquisition - the process of extracting, structuring, and organizing knowledge from some source, usually human experts, so it can be used in a computer program.

knowledge structures - the representations created via the process of concept mapping, the result of negotiated understanding between the knowledge engineer and the subject matter expert, used by the knowledge engineer to communicate system requirements to system developers.

problem domain - the problem domain is a sphere of understanding or range of problems associated with a specific field.

problem space - the problem space is a conceptual subregion within the problem domain that is defined and bounded by the dimensions of the problem.
production and use oriented aspects of design - the set of subproblems within the design process which either produce the physical instantiation of the conceptual process or is related to the subsequent use of the artifact (simulator).

Delimitations

Subjects

The subject population chosen for this investigation was aerospace crew system designers primarily from Wright Research and Development Center/Cockpit Integration Directorate, Crew Systems Concepts Branch (WRDC/KTC) and Midwest Systems Research, Inc. (MSR) at Wright Patterson Air Force Base, Ohio (WPAFB). Subject sample size for the integration meeting data was limited to seven by the size of the design team. Subject designers from Armstrong Aerospace Medical Research Laboratory (AAMRL) and other contractors were included only in the interview and design diary portion of the investigation as they were not a part of the design team.

Design Process

The design process studied follows a systems approach defined by Kearns (1982), and further discussed by Moss & Hudson (1983). Only the function and information analysis portion of the design process was observed for the purposes of data for this dissertation, although this investigator has
continued working with the design team, observing the transition to design synthesis and evaluation.

This design team's focus was on the development and testing/evaluating of crew system concepts for next generation aircraft. The aspects of the work that were not obtained include meetings among/between members of the group outside of the integration meetings, and observations of individuals doing work alone.

Limitations

The following are known or expected limitations of the methodology, which might have affected the results.

1. The approach adapted for the examination of the individual information seeking behavior and group problem-solving behavior of designers in their work setting, was a result of no prior methodology for assessing these behaviors to guide this work. Therefore, the reliability of the techniques was unknown.

2. Protocol analysis limitations applied because the validity of the questions extracted as data for this study fall under the same suspicion as protocol data.

3. The study was of the nature of an extended case study, making generalization of results to other design groups limited.

4. The proprietary nature of the work done by the support contractor personnel who were participants may contribute
to false findings in that the designers, particularly in the interview context, may be less than fully cooperative.

Assumptions

The following are key assumptions concerning the methodological approach:

1. The question asking behavior of designers is closely related to the knowledge they possess. This is supported by the findings of Miyake and Norman, (1979); Schank (1989); Graesser (1985); Larkin (1983); and Lehnert (1978).

2. Assumptions of protocol analysis (Ericsson & Simon, 1984):

   The information processing perspective was not precisely the perspective for this study, which was closer to a language/action perspective such as that described by Winograd, (1988), however, the following modifications of the assumptions put forth by Ericsson and Simon (1984) apply:

   a. The subject's behavior can be viewed as a search through a problem space, accumulating knowledge and seeking information which can be represented by a problem behavior graph. In
this case the problem behavior graph takes the form of question concept maps.

b. Each step in the process involves the application of an operator to knowledge held in short term memory (STM). Thus, short term memory limitations such as Miller' (1956) 7 +/- 2 apply, especially with respect to the error analysis of the data.

c. Verbalizations of subject's correspond to some part of the information currently held in STM.

The following had no support in literature, but was assumed for this study:

3. The question is an appropriate unit of analysis for describing problem-solving behavior. Although this seems intuitive, it may not be the best unit of analysis.

Analyses

Qualitative analysis

Interaction analysis was applied to the transcripts of the interviews and integration meetings, and to the diary material. In the examination of the meeting transcripts, the investigator focused on detecting problem-solving strategies and patterns of thinking which demonstrated errorful behavior. The analysis sheet responses were analyzed for evidence of different questioning and information seeking strategies utilized by different designers.
Question concept maps were created for a subset of the interview questions which were subjected to the analysis sheets. These are presented along with design team member comments. Support system developer comments about question concept maps as a communication support tool are reported.

Quantitative analysis

Counts of questions were generated for the interviews, diaries, and integration meetings. These were broken down as: (1) total number of questions analyzed; (2) total number of interview questions; (3) total number of integration meeting questions; and (4) total diary questions.

The rate of question-asking was generated for each of the knowledge acquisition methods as a comparison of the efficiency of the methods in terms of acquisition of questions. The interview/analysis sheet data were subjected to correlation analysis, row by column, that is, category by subject to examine similarities between/among subjects in question asking, information seeking, and problem-solving behaviors.

Overview of the Dissertation

Chapter I provides an explanation of the need for the study, states the problems to be solved, defines relevant terminology, bounds the problem space by providing delimitations, limitations and assumptions relevant to the
study, and outlines the analyses which will be applied to the data. Chapter II provides a review of the relevant literature, expanding/explaining the choice and development of the knowledge acquisition tools and techniques, and the question concept mapping approach. Chapter III presents a description of the methodology used in the study. Chapter IV presents the data and the findings. Chapter V reviews the conclusions and presents recommendations for future use and extension of the tools and techniques. The appendices include selected samples of the raw data, copies of the data collection tools, and samples of question concept maps.
CHAPTER II
LITERATURE REVIEW

Introduction

Included in this chapter is a review of the relevant literature. The design process as prosecuted by the target population is examined. The need for design support systems and requirements for the identification of their makeup are reviewed. Literature pertaining to design team communication problems and a method for enhancing design team communication is examined. The understanding of the cognition of design is addressed, and methods for the acquisition of design knowledge are reviewed.

Design as Prosecuted by the Target Population

In a report describing the crew system design process, written by one of the foremost experts in the area of crew system design, references were made to doing mission analysis, function analysis, information analysis, and analyzing the technology base, and methods were discussed for doing these (Kearns, 1982). When the time comes to put the design together, however, the generation of control/display layout and the generation of the control/display concept is gotten at
by having "the crew system designers well steeped in the problem." (Kearns, 1989). Design is prosecuted via a systems approach. This approach to crew system design was attributed to Kearns in a report by Sexton (1988) who also stated that variations of this methodology have been and are being used by several major aircraft manufacturers. In discussing the synthesis phase, Sexton said "Design team members conceptualize the aircraft design by using mission scenarios as drivers. Forecasts of user needs, the operating environment, and available technologies applicable to the time frame are all design considerations."

Design, as currently practiced, particularly in the defense world, and specifically in the subject population, follows a general sequence (Abbott, 1989; Eggleston, 1987; Moss and Hudson, 1983; Kearns, 1982). There is a definition of system objectives, derived from a statement of need, mission employment needs statement, and discussions with current users.

A function analysis, often matched against one or more mission scenarios determines what the system needs to do in order to be able to achieve the identified system objectives, and is often followed by man-machine function allocation.

An information analysis determines what information either the system or the operator will require in order to complete a function or determine that a function is needed, and identify the characteristics of the required information
such as granularity or level of precision, trend, range of use, and number of dimensions.

The possible display and control technologies are identified via a technology assessment, and the possible modes of information presentation are listed. Next, the form of the information begins to be specified, i.e., graphics symbols representing certain types of information are created or selected from pre-existing symbol libraries, or a determination that alpha-numeric presentation is better than graphic presentation.

This preliminary specification is then subjected to the implementation constraints for the system of interest. The control or display concept must now be modified to conform to the identified constraints. Control/display definition, constraint identification, modification of controls/displays, prototyping of the displays/control, and evaluation of prototyped materials continues iteratively until the design is proven unacceptable or has reached (for this aggregation) an "optimum" combination.

Need for Design Support Systems

There is a need for information support systems for designers (Doppelt, 1988; Rouse and Boff, 1987), and a lack of knowledge of the cognitive processes of design (Malhotra, Thomas, Carroll, 1980; Carroll, Thomas and Malhotra, 1979; Fawcett, 1987; Magee, 1987). The knowledge of cognitive
processes should be based on the observation and evaluation of the crew system design process (Norman, 1986). One form of support needed was presented by Rouse and Boff (1987) citing a need for developing knowledge based information processing methods to help designers keep track of relations among interdependent design issues.

Crew system designers do not have adequate time or resources to generate all possible combinations of design solutions because the number of variables which could be manipulated will result in a combinatorial explosion, much less compare and evaluate each combination. Support systems should be built based on "...the development of methodological tools to examine the key decisions and define the information that can or should be made available to them." (Keen, 1978)

A review of the tools (Richards, 1982; Bailey, 1982; Barthelemy, 1990) used to support the crew system design process, and of university catalogs in which engineering design in many subdisciplines are taught revealed that crew system design is in much the same state as recognized by McFarren (1987) for the design of decision support systems. The key insight was that the vast majority of the tools with which design engineers work and the techniques which they are taught are analytic techniques, and that this seems to be independent of domain.

The idea of the prevalence of analytic techniques is not new. Simon (1981), spoke of the same problem, saying "...in
view of the key role of design in professional activity, it is ironic that in this century the natural sciences have almost driven the sciences of the artificial from professional school curricula. Engineering schools have become schools of physics and mathematics.... The use of the word "applied" conceals, but does not change the fact. It does not mean that design is taught, as distinguished from analysis."

Cody and Rouse (1987) in summarizing the lessons learned resulting from extensive interaction with crew system designers, defined crew system designers as "...those individuals who intentionally influence the form or function of the entire crew system or its components. These designers came from Boeing, McDonnell Douglas Aircraft, McDonnell Douglas Helicopter, Lockheed-California, Lockheed Georgia, Singer Link, the Naval Training Systems Center and others. They reported that two major reasons explained the phenomena they refer to as the "elusive designer", which had them talking to a wide variety of (designer) sources in response to their request to the various organizations for access to persons doing crew system design. First, the crew system is the composition of six ingredients, each of which is governed by several technical disciplines. The six ingredients are derived with reference to their definition of crew system (referred to variously as "cockpit", "crew station", "flight deck", "pilot-vehicle interface", and "crew System". These six include: selection, training, equipment
design, job design, aiding and protection. The coexistence of individuals on a design team whose educational backgrounds differ creates a multidisciplinary language barrier (Boff, 1987), and brings together individuals whose training tends to be in the utilization of very different sets of engineering tools.

The second reason for the difficulty in identifying who it is that does crew system design is the process by which military systems are born, modified, and eventually, acquired. This takes a long period of time, and allows many people not directly involved in the execution of the final design to intentionally influence crew system design. Both of these seem to be communication problems, the first among team members of varied backgrounds, and the second a traceability type of question.

Cortes-Comerer (1987) supported the position presented by Cody and Rouse (1987) with respect to the need for interdisciplinary approaches to engineering design, and cited the increasingly interdisciplinary nature of design teams. This raises the question - Is this interdisciplinarity adequate to meet the needs left unfulfilled by the lack of synthesis tools or courses to teach synthesis techniques?

One response to this issue, by Debons (1987), in describing intellectual requirements for system design, stated that "... the designer's education and experience, along with a conceptual model of a system, are considered fundamental to
the design process. Because the current academic institutions emphasize discipline-oriented educational programs, the availability of educators to provide interdisciplinary perspective to system design is limited. Departments are inclined to focus on safeguarding existing paradigms."

Question Asking

The question was chosen as the focus for this investigation because of the support from the literature: (1) the questions a person asks were found to be closely related to the knowledge they had (Miyake and Norman, 1979); (2) the generation of questions under artificial circumstances (such as interviews) is more natural than other methods (Kato, 1986); (3) the question is an observable behavior which has observable consequences (Horne, 1983); (4) questions have been the focus for expert systems in terms of question answering (Lehnert, 1978); and (5) it was assumed that all designers ask questions, allowing the question to be the common dimension that links the group in the design process as well as allow for the comparison of individual question asking, information seeking, and problem-solving behaviors. These reasons are supported by more general work concerning questions in problem solving (Winograd, 1988; Graesser, 1985; Reder and Anderson, 1980). A further development of what can be expected through an examination of the question asking behavior of designers follows.
Malhotra et al. (1980), in an examination of the cognitive processes in design, found design cycles that showed a regularity of structure with a diversity of content. The regularity of type of question with differing content might also be expected as the design process continues.

Reeder and Anderson (1980) found that learning from summaries of information is as good as reading original text. Further, they found that those who studied summaries did better with questions taken directly from text, that inference type questions required the subjects to combine facts, and stated that questions appeared to serve as a focal point for the organization of information. This idea of focussing attention via the questions asked may have merit in explaining errors in design. If the wrong questions, with respect to an "optimal" design were asked, the right questions were asked but with the wrong perspective, or the right questions were not asked at all, it may result in information seeking which supplied the correct answer to the question, but which did not enhance the viability of the design. The importance of this point is emphasized by Winograd (1988):

"Within the community concerned with the design of computer systems, there is a growing recognition of the importance of the designer's perspective - the concerns and interpretations that shape the design, whether they are articulated explicitly or are just part of the unexamined background of the work. A perspective does not determine answers to design questions but guides design by generating the questions to be considered."
Bransford et al. (1982) performed a series of experiments on the acquisition of facts in a new field. The research addressed two questions: (1) What are successful learners doing that less successful learners do not do?; and (2) Can the performance of successful learners be improved by modifying their cognitive strategies or processes? They found that successful learners asked many more questions - both of themselves and others around them. They actively worked to relate new information to things they already knew.

Horne (1983) explored information seeking questions in closed problem situations, viewing questions as observable behavioral acts reflecting information need. "Amount" of information need was assessed by Horne via a linguistic categorization utilizing open/closed, saturated/unsaturated, which/whether, and "if" and modal usage, and comparing the number of questions asked to the amount of information provided. The number and type of questions provided insight into the information need. The possible confound here is that design problem solving tends to be ill-defined and open rather than closed.

Miyake and Norman (1979) reported that the ability to ask a question implies more than a simple information need. It requires a structure of knowledge with which to formulate the question and to interpret the response. They showed that the number of questions asked would demonstrate an inverted U function of the relationship between student knowledge and
task complexity. They explained this further by stating the novice does not have the proper (knowledge) framework within which to ask a question. The kinds of questions asked reflect the level of development of the concept which the question asker has attained, and as such, reflects the level of complexity and/or completeness of understanding with respect to the target material. Miyake and Norman (1979), in their discussion of question asking, viewed the number of concepts and hypotheses as reflecting the more salient aspects of questioning behavior..."To create a hypothesis, subjects should have some expectation of inferred understanding beyond the given material: hypotheses thus implying the asker is active in constructing a knowledge structure."

A "theory of asking the right questions" would be extremely important to the enterprise of structuring domains of interest. First attempts at such a theory appear in an essay by Flammer (1981b). However, the methods of questioning and information gathering often will not suffice. How can one structure a field of reality hypothetically, when little is known about it and no information can be recalled from external information banks?

J.W. Getzels (1973) stated:

"The advancement of knowledge and of the quality of life depends as much on the arts of finding and formulating problems as on the technical skills for solving the problems once they are found and formulated. And one might even argue that the ultimate values of a people reside more in the
questions they put to life than in the transitory solutions to which they may be driven."

Information Seeking

Typical activities which are referred to as "real-world" problems are open, often ill-structured, and have multiple "satisficing" (Simon, 1973) solutions. The information seeker/problem solver has a task generated information need, reflecting a lack of knowledge on his part (Flammer, 1981b). This perceived need may take the form of needed facts, specifications, algorithms, or other data of which the problem solver may or may not be aware.

Meister and Farr (1965) reported on the creation of tests to measure the utilization of human factors data by engineers, describing what they expected from questions asked by engineers regarding information needed to complete a design described in a design scenario:

"The kinds of things the designer mentions will indicate the relative priority he gives to various considerations. It is hypothesized that we will get different responses depending on whether the subjects are EE's or ME's, and on the amount of 'practical' experience the subject has."

Meister and Farr (1967), reviewed the results of these tests, and reported designers requested information dealing with strictly functional characteristics, while human factors specialists were concerned with the total system in
operational use and the functions to be performed. They did not report data about the hypothesized differences between ME's and EE's.

Still, the implication and evidence point to different mental models created by different training and experience (Robertson, 1985). These differences give rise to qualitative issues in the need for and the evaluation of accessed information. These include topic, relevance, understandability, usableness in problem solution, and level of complexity. Quantitative issues include such things as time to access, cost, and time to evaluate (which may reflect some qualitative issues). The ease with which the problem solver incorporates information into the problem-solving process depends on the qualitative aspects.

MacMullin and Taylor (1984) defined an information need continuum of problems to questions to sense-making and proposed that problems should be the focus of attention because the user situation or context is intact in the problem. Yet, they later stated that "Questions are the result of the fragmentation of problems and indicate the most precise state of incognizance." However the relations are defined, the close integration of problems, questions, and information seeking is well recognized in the literature.
Problem Solving

Clancey (1986), divided knowledge based problems into analysis (interpretation) and synthesis (construction) problems. Boose (1989) proposed a framework using the major categories of analysis, synthesis, and problems which combine analysis and synthesis. Problems listed as analytic were: (1) classification; (2) debugging; (3) diagnosis; and (4) interpretation. Problems classified as synthetic were: (1) configuration; (2) design; (3) planning; and (4) scheduling. Problems combining analysis and synthesis were: (1) command and control; (2) instruction; (3) monitoring; (4) prediction; and (5) repair. The analytic problems were identified as coupled to heuristic classification problem-solving techniques, while the synthetic problems were linked to heuristic construction techniques.

Problem solving is a pervasive activity of human life. A human has a problem when he has a task he does not know how to carry out, and has some criterion to apply to determine when the task is successfully completed (Simon, 1973). Where do I begin? Where is the starting point? What are the key points of the problem? These are typical questions raised by a person trying to solve a problem. The constraint in the above description of a problem, that the problem solver does not know how to carry out the task, implies a need for either a transformation of information already available to solve the problem or a need for new information.
Typical problems presented to students in the course of elementary, secondary, undergraduate and much of graduate education are of the closed, well-defined type. These problems are typically well structured, and require skill in the application of algorithms to arrive at a unique, correct solution. Problem-solving activities of this type have been extensively studied in science and mathematics education and are useful in understanding how to better facilitate the learning of these skills. Very few teachers teach the skill of defining problems (Keen, 1978).

Heuristic was defined as the science of finding solutions to problems whenever there are no algorithms by Dorner (1983). An algorithm is a formula for a solution (i.e., a plan for the sequence of steps required in order to find a solution with certainty if one exists). A heurism is also a plan, that is, a formula for a sequence of steps taken when working out a solution. In opposition to an algorithm, however, heurisms do not offer an a priori guarantee that a solution can be found, if one exists. Conflicts between goals are not unusual when dealing with complex goals, due to conflicting relationships between subgoals. Subgoals must be weighted, and under certain circumstances, it might be necessary to either partly abandon a subgoal or give it up completely.

The problem solver normally does not have knowledge of the complete set of operators with which the situation can be altered (Dorner, 1983). For one thing, he usually does not
know all the possible steps he can take. Secondly, he does not exactly know which effects the operators will have, even if the operators themselves are known to him. This is the case because the situation within which one has to understand and act may not be exactly clear (i.e., the conditions for applying the operators is uncertain). It is often necessary to act, although some information that is actually needed is not available. In such situations, the information at hand is often incomplete and therefore unsatisfactory. This implies that one must act on the basis of incomplete and inexact information. Furthermore, it is usually the case that one is doubtful as to whether the information one has is correct or incorrect.

The characteristics of ill-defined problems mentioned previously - vague goal criteria, multiple goals, lack of knowledge of the structure of the system one must work within, and lack of knowledge as to the present state of the system are typical features of situations which individuals must deal with in very complex, dynamic systems. They are characteristic for the demands placed on thought and action in such fields of reality as for example politics, economy, and ecology, not to mention the control of nuclear power plants or fighter aircraft.

The demand of making goals precise comes from the situational feature of an open goal (Dorner, 1983). Conflict between goals, created by the interaction of multicomponent
goal situation and the network structure of reality, raise the demand of tradeoffs among goals. If the problem solver concentrates on points of main effort, the necessity of background control arises, for it is dangerous to neglect certain parts of the reality. Some of these demands incorporate knowledge demands of their own. Very often it is necessary to increase the knowledge about the systems' structure.

There are two problems that are enclosed within the demand to increase structural knowledge (Dorner, 1983). The first one is how can I get information; the second problem is to what grain, to what resolution level, should one continue to collect information. This second problem is essentially the question of establishing a stopping rule for gathering information.

The first and easiest possibility of structuring an unknown partial system is to gather information about the unknown area; reading and questioning (Dorner, 1983). More essential is to know how to put the right questions to the right persons and how to read the right books. A second way of adding structure is to use an analogy to transforming the structure of a known field of reality onto an unknown one.
Generating Support System Requirements from Error Identification

Problems arise in the design of complex systems (Sexton, 1988). The complexity extends beyond the ability of the human mind to cope with simultaneous understanding of all of the variables, much less the interactions. Miller's (1956) famous 7+/-2 concept provides an explanation of these difficulties in terms of the information processing paradigm indicating that there was a limit to the amount of information that could be processed in short term memory.

Human information processing difficulties such as these limitations on short term memory capacity and the slowness of manipulation of information in short term memory (compared to computers) can be supplemented by what Zachary (1986) referred to as information-control techniques which help with representation, manipulation, access, and monitoring of bodies of data and knowledge.

The technique of understanding the origin of cognitive errors and developing methods for reducing errors through support system design was advocated by Lewis and Norman (1986).

Information Seeking Effort

The lengths to which designers would go in order to pursue information should have implications for the creation of design support tools. Allen (1977), found that frequency
with which information seekers access sources varied approximately inversely with the distance needed to travel to access it.

**Design Team Communication Problems**

The difficulties in the access and use of information arise in particular when the information needed is of a cross-disciplinary nature (Boff, 1987). Boff (1987) addressed questions of information access, interpretation, and use with particular reference to the use of human factors data in the design of Department of Defense systems. The access, interpretation and use problem was recognized by Meister and Farr (1965) and has persisted (Havelok, 1966; Meister and Sullivan, 1967; Meister and Farr, 1967; Lintz et al., 1971; Rouse, 1936; Sage, 1987; Aluissi, 1987).

One response to this issue, by Debons (1987), in describing intellectual requirements for system design, stated that "... the designer's education and experience, along with a conceptual model of a system, are considered fundamental to the design process. Because the current academic institutions emphasize discipline-oriented educational programs, the availability of educators to provide an interdisciplinary perspective to system design is limited. Departments are inclined to focus on safeguarding existing paradigms."

Debons (1987) made an explicit distinction between multidisciplinarity and interdisciplinarity.
Multidisciplinarity was defined as a variety of disciplines offered simultaneously without making explicit possible relationships between them. Interdisciplinarity, then, was defined as a group of disciplines related at the next higher hierarchical level, such as crew system design, which introduces a sense of purpose. He made the claim that two realities exist which require reconciliation. These were (1) the fact that the design of systems is a practical, operational activity, and (2) that the intellectual process which defines interdisciplinarity is synthesis. The lack of interdisciplinary education, resulting in the isolation or definition of a system in terms of a single component (e.g. multifunction display, radar, control stick) does not comply with the spirit of the systems approach and was viewed by Debons as seriously impacting the system design process.

This communication difficulty could be explained in terms of knowledge structures and the use of information by persons not of the discipline of origin of the information (which is the case with the design group that is the subject of this study). Zachary (1986) provided an analysis of the use of information in decision making. He defined information as data that has been interpreted by the decision maker in the context of knowledge about the decision environment. In this, he agreed with Rabins (1986). Further, Zachary (1986) stated that knowledge refers to cognitive propositions about classes
of information used to reason with and understand a body of information. Zachary (1986) analyzed the problem further.

"Although historically the most common information problems in decision making were insufficient and/or uncertain data, new information-processing technology has made data overload the more common problem. This has created knowledge problems in which the decision maker is required to interpret so much data so rapidly that the key piece of knowledge is never applied to the key datum. The result is that the person does not perceive a crucial piece of information, even though the necessary data and knowledge were available."

These control mechanisms or problem-solving strategies are based on domain-specific ways of reasoning with and analyzing a particular style of problem representation learned through experience in that domain (context). This seems to be a key in the difficulty facing the interdisciplinary information seeker - the lack of understanding of context. Given the increasingly interdisciplinary nature of design teams (Cortes-Comerer, 1987), and the findings of Kasperson, (1978) of the need to access multiple sources of information, the ability to effectively communicate will become increasingly important.

The communication problem between knowledge acquisition personnel and the system development team, difficult even when design teams are in close proximity to the users of the system, is exacerbated when the design teams perform their work in a location remote from the actual site of use of the design artifact (Bannon, 1986).
Concept Mapping

"The basic idea in understanding, whether by computer or by people, is first to figure out what concepts are being communicated and then to use those concepts to help in figuring out what else might be the case. Once we know there was a 'giving' action, we know that there was a 'taking' and a 'receiving'; we know that there was an object and that someone now has it and will probably use it for whatever it is normally used for. Ascertaining this kind of information is what understanding is all about." (Schank, 1987).

"Concept mapping is an educational tool that has been developed specifically to tap into a learner's cognitive structure and to externalize for both the learner and the teacher to see 'what the learner already knows.'" (Gowin, 1982). A concept map is two or more concepts that are linked to each other by some meaningful relationship in the form of a proposition. Propositions are two or more concept labels linked by words in a semantic unit. Concepts are viewed as objects or events of varying complexity which are identified by a semantic label. Link labels may be verbs, adjectives, adverbs, prepositions, and phrases.

Problem understanding is dependent upon the ability of the designer to use the language of design and organize facts in the description of the problem (McFarren, 1987). Concept mapping can be used to combine both words and images to describe the design problem. The map provides a representation that is not restricted to a linear (textual) presentation. This type of description may provide the first step toward improving the design process by externalizing a
concrete representation of the verbalized problem-solving behavior to support communication. Concept mapping is a tool which has been proven effective of relating new concepts and relaying their meanings to students (an exchange of the understanding of a knowledge structure).

**Need for Understanding the Cognition of the Design Process**

As noted in Chapter 1, a growing number of builders of human-computer systems have noted the central role the user should play in the design of the system (Norman, 1986; Booth, 1989; Winograd and Flores, 1987). The assessment of the users' cognitive structure has implications for general system design and training (Hall et al., 1981), the knowledge acquisition process in the building of expert systems (Ericsson and Simon, 1985), information system design (MacMullin and Taylor, 1984), and the design of human-machine cognitive systems (Woods, 1986; Norman, 1986). Graesser (1985) cited the need for a theory or model of question-asking and question-answering to provide direction to these kinds of functions.

Mostow (1985) raised several general issues with respect to needs for improving the design process: (1) cognitive models of design deserve further investigation; (2) techniques for acquiring design knowledge need to be developed; and (3) the goals of knowledge acquisition behaviors such as
information seeking are important in the representation of the design process.

Rabins (1986) cites research needs for "intensive descriptive studies of successful designers and design behavior", and "intensive descriptive studies of design expertise". These descriptive studies should include "exploration and evaluation of flexible methods of problem definition", "research on team design", and "study of the use of information in design".

Psychology of Design

Investigations into the psychology of design have generally provided design scenarios, and asked subjects to respond to these under relatively controlled conditions. Most are either architectural, hardware, or software design (Eastman, 1968, 1978; Malhotra et al., 1980; Carroll et al., 1979; Cohen et al., 1986a; Cohen et al., 1986b, Eckersley, 1988; Newland et al., 1987). None of the reviewed analyses investigated group design problem solving. One reference was found (Mittal and Dym, 1985) which addressed the acquisition of knowledge from multiple experts, but the objective was to build an expert system which captured and modeled their combined expertise as compared to the capture of knowledge for the purpose of system design. These could be expected to be quite different, both in the structure of knowledge and
methods which are appropriate to the acquisition of knowledge (McCracken, 1990).

Eastman (1968) used protocol analysis within an information processing paradigm on four architectural design tasks, identifying language as having a significant influence on problem solving in design. Eastman (1978) discussed the representation of design information in abstraction hierarchies for implementation in a database environment to support design, again, a language oriented approach.

Design style was objectively assessed by word counts - total words, total unique words and words per sentence, finding 50 to 60% differences between a software design group labeled programming style when compared to a group labeled narrative style by Malhotra et al., (1980). Observations of the parts of speech classes for the same data also suggested stylistic differences.

Variations in individual differences in the cognitive/linguistic processes of designers have therefore been dealt with via analysis of verbal behavior. These individual differences have implications for information system design (Benbasat and Taylor, 1978). The general lack of literature on the cognition of design and the relative simplicity of the domains upon which previous work had focused turned the investigator to a more general approach.
Models of Question Asking

Stillings et al. (1987), declared that much of human thought involves manipulating knowledge structures to decide what to do, predict occurrences, deduce reasons for events which have occurred, etc. This allows humans to make predictions about (understand) their world, and to plan actions during everyday life. In this section, a review of the development of the notion of a mental model and an examination of some of the implications for the present work are presented.

Cognitive Psychology and Mental Models

In some of the earliest work on mental models, Craik (1943) proposed that thinking is the manipulation of internal representations of the world. Craik (1943) wrote that human beings were information processors, making use of three different processes. These were: (1) translation of external events, objects or processes into an internal (mental) representation in terms of words, numbers, or other symbols; (2) other symbols can be derived from these first order symbols by some process of inference; and (3) these symbols can be re-translated into actions or a recognition of the correspondence between these internal symbols and the external events, objects, or processes which allowed for the realization that a prediction is fulfilled. Craik (1943) wrote:
"My hypothesis then is that thought models, or parallels, reality - that its essential feature is not 'the mind', 'the self', 'sense-data', nor propositions but symbolism, and that this symbolism is largely of the same kind as that which is familiar to us in mechanical devices which aid thought and calculation... If the organism carries a 'small-scale model' of external reality and of its own possible actions within its head, it is able to try out various alternatives, conclude which is the best of them, react to future situations before they arise, utilize the knowledge of past events in dealing with the present and future, and in every way to react in a much fuller, safer, and more competent manner to the emergencies which face it."

Much of the research into the nature of mental models from 1943 to the publication of two books with the title Mental Models (Gentner and Stevens (1983), and Johnson-Laird (1983) was in the domain of cognitive psychology. This research largely centered on the study of research on concepts, and is typified by the work of Rosch and Mervis (1975) on families of categories, Collins and Loftus (1975) on semantic networks, Anderson (1976) on the effect of elaboration networks on memory, Bower, Black, and Turners' (1979) work on scripts for everyday phenomena, and Barsalou (1982) on contextual priming on network components.

Cognitive Science and Mental Models

Johnson-Laird (1983) proposed a set of principles for the construction of mental models. These included the principle of: (1) computability; (2) finitism; (3) constructivism (a mental model is constructed from tokens arranged in a
particular structure to represent a particular state of the world); (4) economy in models; (5) mental models being able to represent indeterminacy only if there is not an exponential growth in complexity; (6) predicability (one predicate can apply to all terms to which another applies, but they cannot have intersecting ranges of applications); (7) innateness; (8) the existence of a finite set of conceptual primitives which give rise to a corresponding set of semantic fields and that there is a finite set of semantic operators that occur in every semantic field; (9) structural identity (the structures of mental models are identical to the structures of the states of affairs, whether perceived or conceived, that the models represent; and (10) set formation (if a set is to be formed from sets, the members must be specified first).

Principles Six and Eight need further explanation. Predicability can be understood as a principle of logic. For example, Ohioan and American apply to certain things in common. American applies to some things to which Ohioan does not apply, but there is no-one to whom Ohioan applies and American does not. This principle can be applied to the construction of sets in that a set would be considered artificial or unnatural if the predicability constraint is violated. The set {26, hammer, Easter bunny, scotch, red, knees} is artificial, because its members have nothing in common.
Artificial Intelligence and Mental Models

The field of artificial intelligence (AI) makes use of the notion of mental models in a way that is slightly different from the psychology or cognitive science approach. In contrast to the world of psychology with its orientation to statistics, and the resultant requirement for numbers of subjects, the AI world tends to derive its models from a limited number of individuals, sometimes with an n=1. These models are described as providing metaphors for generation of intelligent systems (Chandrasekaran, 1981). More recently, the work of AI has been extended to providing a comprehensive "cognitive architecture" for intelligent systems (Laird et al., 1987). In general, the focus is on the construction of systems that embody intelligence in some way.

Mental Model Interpretation and Use

Regardless of which paradigm for the construction of mental models is employed, there are some general characteristics of mental models that are common to each. In 1983, Gentner and Stevens wrote that there were three key dimensions by which research into mental models could be characterized. These were the nature of the domain studied, the theoretical approach, and the method used to capture the mental model.

Gentner and Stevens (1983) described the domains which had been approached by mental model researchers at that time;
they listed mostly technical domains in the physical sciences, stating that the reason for this was precisely because those problems which could be solved by the methods of physical science were the ones which had available the best normative models. The theoretical approaches for the representation of knowledge tended to be based on computational semantics developed within the community of artificial intelligence research. The methodologies used to collect the knowledge to populate the representation structures were described as eclectic.

Johnson-Laird (1983) proposed as semantic fields shape, color, person, kinship, motion, perception, cogitation, emotion, bodily action, possession, and communication. The semantic operators include concepts of time, space, possibility, permissibility, causation, and intention. These principles provided a framework within which to construct mental models and against which to judge the adequacy of a model.

Small scale models, like concept maps, need not be complete. Johnson-Laird (1983) wrote that:

"Like clocks, small-scale models of reality need neither be wholly accurate nor correspond completely with what they model in order to be useful. There are no complete mental models for any empirical phenomena. What must be emphasized, however, is that one does not necessarily increase the usefulness of a model by adding information to it beyond a certain level." (authors' influence on level) A model has ... a similar relation structure to the process it models, and hence it can be useful explanatorily; a simulation merely
mimics the phenomenon without relying on a similar underlying relation-structure."

Small scale models, like concept maps, should satisfy the similar relation structure constraint identified above, and be verifiable as representing the cognitive process by the subject who produced it. The generation of such a concrete representation provides an external referent which can be used as a space in which understanding can be achieved between the subject matter expert and the knowledge engineer.

Level of Description of Mental Models

Greeno (1983) discussed the differentiation of representations by the kinds of entities which are included in the model. The question was chosen as the unit of analysis and the entity of synthesis for this dissertation.

Mental Models and the Cognitive Engineering of Systems

The notion of mental models has been shown to be well established within the literature of psychology, cognitive science, and artificial intelligence. The concept of the mental model is beginning to be used to guide system design. Rouse and Morris (1986), in a review of the mental model literature specifically inquiring into the utility of the mental model notion for the purpose of system design, included material from supervisory control, cognitive psychology,
cognitive science and artificial intelligence. They proposed a definition that "Mental models are the mechanisms whereby humans are able to generate descriptions of system purpose and form, explanations of system functioning and observed system states, and predictions of future system states." They identified methods for the study of mental models which included inferring their characteristics via empirical studies, empirical modeling techniques, analytical modeling, and verbal/written reports.

Norman (1986), in discussing the use of mental models as tools for use in the cognitive engineering of systems stated:

"Mental models seem a pervasive property of humans. I believe that people form internal, mental models of themselves and of the things and people with whom they interact. These models provide predictive and explanatory power for understanding the interaction. Mental models evolve naturally through interaction with the world and with the particular system under consideration. These models are highly affected by the nature of the interaction, coupled with the person's prior knowledge and understanding. The models are neither complete nor accurate, but nonetheless they function to guide much human behavior."

Norman (1986) indicated that he had two major goals in mind when he coined the term cognitive engineering: (1) understanding the fundamental principles behind human action and performance relevant to development of engineering principles of design; and (2) to devise systems that are pleasant to use - not efficient, not easy, not powerful, but pleasant.
Smith et al. (1986), working with a knowledge based information retrieval system, discussed the development of a mental model that guided users in interpreting and predicting the behavior of the system. They cited Moran's (1981) requirement that the model must cope with different levels of the system's design, with the example that at one level, the user needs to know something about the intelligence built into the system and at another level, how to enter a command to execute some procedure. This idea of levels of the system could also apply to the problem of levels of automation in complex systems such as nuclear power plant, chemical and petroleum process control, and fighter cockpits.

Klein (1990) made the point that as technology emerges, during the test and evaluation phase, knowledge of this system image and its interaction with humans should be captured, and bundled with the technology itself in order to make the technology transfer process smoother. In order to meet these demands, a step is required in the knowledge engineering process to provide a cognitive model which the design/development team can use as a negotiating space as suggested by McFarren (1987), and which can then be modified by the initial users of the system to improve the technology transfer process, as Klein (1990) suggested.

Rouse and Morris (1986) identified issues they believed to be dominant themes in the mental model literature in a variety of domains, citing accessibility of the mental model,
forms and context of representation, nature of the expertise (novice vs expert), effects of cue utilization in the stimulated generation of model components, and instruction. These issues bear on the emerging discipline of the cognitive engineering of systems.

**Question Asking and Role on the Design Team**

Information, as used in design, may be viewed as interpreted data. As such, the source, uses, dependencies on context, etc. must be carried with the data. This information is the key to the role of data in design (Rabins, 1986). Even with identical data, it should be expected that different designers would use that data differently due to differing individual experience. Information needs to be shared between disciplines and within disciplines (Rabins, 1986) and problems arise in the cross-disciplinary access and use of information (Boff, 1986). This is a communication problem, not a problem of intelligence.

**Information Seeking Strategies**

Letovsky (1986) defined inquiry cycles which included hypothesis formation, question asking, and information seeking in the domain of software program design.

Krause and Hagendorf (1986) discuss various information search strategies stimulated by question asking in interactive
They discuss the implications of the individual differences found for the design of methods to access data, information, or knowledge.

Methods for the Acquisition of Design Knowledge

The general problem was that of developing knowledge acquisition techniques and tools for the purpose of supporting system design. This is differentiated from knowledge acquisition for creating an expert system which captures applied domain expertise for use in the creation of a computational emulation of an expert. Additionally, the immediate goal was to build a cognitive rather than a computational model. Gruber and Cohen (1987) described their view of the knowledge acquisition process as one of representation mismatch, stating that the primary contribution of design for knowledge acquisition is to make the notation for expressing the knowledge more comprehensible and accessible to the experts whose knowledge is being accessed.

A review and classification of 65 tools at the Third International Workshop for Knowledge Acquisition (Boose, 1989), revealed a void in the area of tools supporting knowledge acquisition for synthetic problems which are linked to heuristic construction techniques. This is emphasized in the discussion section where Boose (1989), suggesting promising areas for new research posed the question "For example, can special types of knowledge acquisition tools be
associated with debugging problems and heuristic classification, or with planning and new specializations of heuristic construction?" Recall that heuristic construction problem-solving techniques were earlier related to design problems. Human-system interface design, of which crew-vehicle design is a subset, thus falls into this unexplored area.

The review of knowledge acquisition methodologies revealed no single technique that was adequate to the task of acquiring and representing the knowledge structures and information seeking behavior of designers during design problem solving (McCracken, 1987a; Boose, 1985; Boose, 1986; Boose, 1989). The review by Boose (1989) further showed that almost no knowledge acquisition techniques or tools dealt with the problem solution category of heuristic construction, which is the technique proposed for design problems. Included in the review were computer based, interactive knowledge acquisition techniques (Boose, 1989; Martin and Oxman, 1988; Hayes-Roth et al., 1983).

Existing General Knowledge Acquisition Tools

Knowledge acquisition, defined with respect to the domain of expert system building is the acquisition of knowledge, experience, and rules of thumb from a human expert (Martin and Oxman, 1988). Knowledge acquisition, however, has been carried on for some time by several disciplines utilizing a
wide variety of techniques intended to support various purposes prior to the collection under this term with the advent of expert system development. A classification scheme has been offered by Hoffman (1987) which included the following method categories: (1) method of "familiar tasks"; (2) structured and unstructured interviews; (3) limited information tasks; (4) constrained processing tasks; and (5) method of "tough cases". Hoffman (1987) suggested that expert tasks typically involve: (1) analysis of the complexity of the job environment into relevant features or cues; (2) generation through analysis of these cues of conceptual categories; (3) generation of relationships - causal laws - between/among the categories; and (4) the ability to infer and test hypotheses.

In conjunction with Hoffman's (1987) classification scheme, it is suggested that there exists in the literature a variety of tools or techniques for the capture of expert knowledge while the expert is being observed under one of the methodologies designed to expose his expert knowledge. These techniques vary in the degree of interactivity required between the subject matter expert and the investigator, and in the degree to which the analysis is done by automated methods or by investigator analysis. It is necessary for the knowledge engineer to select from these or create tools and techniques for knowledge acquisition in conjunction with methods of exposing the expert's knowledge, to adapt to a given problem-solving environment.
The investigator conducted a review of both general purpose knowledge acquisition tools and techniques as well as those adapted for computer interactive knowledge acquisition. Some of these techniques involve support for the structuring of acquired data. The general purpose techniques included Pathfinder (Schvaneveldt, R.W., Durso, F.T., Goldsmith, T.E., Breen, T.J., Cooke, N.M., Tucker, R.G., and DeMaio, J.C. 1985), interview methods (Bradshaw and Boose, 1989; Trimble and Cooper, 1987; Kidd and Cooper, 1985; Hoffman, 1987; Martin and Oxman, 1988; Kerlinger, 1973; Waldron, 1986), Crawford slip (Crawford, R.P., 1983; Rusk and Krone, 1984), Delphi (Saaty, T.L., 1980), repertory grids (Boose, 1988; Kelly, 1955); protocol analysis (Ericsson and Simon, 1984); and concept mapping (McCracken, 1987a; McFarren, 1987). Literature related to the methods selected for this study are reviewed briefly.

Interviews

Interviews can be used for three main purposes: (1) as an exploratory device to identify variables and relations; (2) as the main instrument of research; and (3) as a supplement to other methods - follow-up, validation, and exploration in depth of motivation for responses (Kerlinger, 1973). Interviews can be of two types - structured or unstructured. Structured interviews have a fixed schedule of questions, that is, the sequence and wording are fixed for all subjects to be
interviewed. Four basic types of questions can be included in the interview whether it is structured or unstructured: fixed alternative or closed questions, open-ended questions, scale items, and probes. Probes can be either reflective or request questions. Care must be taken to write questions which focus on the goal of the research project, are clear and unambiguous, and are not leading or loaded. Because the interview is a direct method of knowledge acquisition, that is, the researcher in contact with the subject, it tends to yield more information than indirect methods, probably due to the social interaction involved. The main weakness of the interview method is that it is very time consuming, both for the researcher and the subjects. This is particularly true when the interviews are taped, transcribed and analyzed.

Concept Maps

Concepts maps have been discussed previously, and will be referenced here as being used as knowledge acquisition devices by McFarren (1987).

Observation and Participation

Investigator observation and participation was discussed by Lincoln and Guba (1985). They strongly suggest film or videotape for recording activity when at all possible. Additional records suggested to be generated for a field study included: (1) running notes; (2) field logs; (3) chronologs;
context maps; (4) categorical notes or entries; (5) relation
diagrams; (6) debriefing questionnaires for the investigator
to serve as reminders of categories to record notes; and (7)
rating scales or checklist.

Interaction Analysis

Interaction analysis involves the examination of transcribed verbal data. These data may be generated in a variety of ways. It can be either audiotape or videotape of subjects responding to interview questions, working at individual problem solving in a controlled environment, working in group doing problem solving or supplied retrospectively. Interpretation of the data involves generating a unit of analysis or focus, structuring the data into classes, extracting the members of the class from the data, and generating explanations for the content and structure of the result. Interaction analysis is time-consuming and is subject to question about inadequacies with respect to subjects' ability to verbalize.

Summary

The need for systems which support designers is not new. Computer-aided design stations have been around for years. However, the generation of tools for the cognitive support of design is only now beginning to emerge. No a priori stance was taken for this study concerning the nature of the possible
support systems or tools. This stance was taken for two reasons. First, the difficulties cited by Buchanan et al., (1983), which included: (1) representation mismatch; (2) problems in verbalization by the expert; and (3) limits on current technology for developing expert systems, particularly in the area of heuristic construction.

Second, there was no evidence in the form of data from other studies of crew system designers as to the structure of knowledge or problematic areas on which to base hypothetical areas of support or potential support systems or tools.

The set of methods was selected as generating an integrated set of data from a variety of sources, paralleling the Halpern Audit Trail process (1983) for descriptive research in "naturalistic settings" as described in Lincoln and Guba (1985). This will be described in detail in Chapter III - Methodology.
CHAPTER III

METHODOLOGY

Introduction

This chapter presents the methods used in this study for acquiring, analyzing, synthesizing and communicating design problem-solving knowledge and information seeking behavior. The generation of a set of methods was Problem 4 for the present study. First, a description is provided of the subjects of the study, and the equipment needed for the study is described. The paradigm within which the study was done is reviewed. The methods for knowledge acquisition, including the instruments (forms and schedules), and procedures (interview, observation, participation, etc.) are presented for both individual and group problem solving. Finally, the qualitative and quantitative methods of data analysis and data synthesis are described.

Subjects

The subjects for the study ranged in age from 25 to 67, the average age was 39. Eighteen subjects were interviewed, seven of those were selected for participation in additional
forty eight interviews, analyses, and observation. The education of the subjects ranged from B.S. to Ph.D. Degrees earned include experimental psychology, aeronautical engineering, industrial engineering, human factors engineering, aviation management, and systems engineering. Experience ranged from 2 to 37 years, with an average of 13.8 years. The subjects included Air Force, government, and contractor personnel. More detailed information is available in Appendix C. All subjects signed a standard release form. A copy is presented in Appendix A. Subject Profile Forms (Appendix B) were generated and used to collect the data provided above.

Both the Flight Dynamics Laboratory (building 146) and the Armstrong Aerospace Medical Laboratory (building 248) were located at Wright Patterson Air Force Base, Ohio. These were the physical location of the designers who participated in the study, although contractors had additional workspace at off-base sites. An more extensive description of the type of work done at these locations is provided in the Context Document (Appendix D).

Equipment

A Lanier microcassette recorder and transcription machine were used for collecting the audiotapes of the interviews and design team integration meetings, and transcribing them into hard copy. Each tape was dated, numbered and coded by subject
number, transcribed and edited. The transcripts were created using Microsoft Word on an ASD microcomputer. This processing included initial transcription, editing, changing the initial files, and printing. The completed transcripts were stored in five 4-inch ring binders. Two 4-inch ring binders were used to collect copies of all of the documents the design team produced during the data collection period. These were used along with the field notebooks to provide the investigator with an as complete a record of the observation period as possible.

Material collected included working function analysis hierarchies, design team memos, the technology assessment, copies of scenarios, information analysis worksheets, journal articles or other references on levels of automation, workload and other topics, which the team used as common references, design team time lines (schedules), and the pilot handbook from the previous generation of the Tactical Aircraft Cockpit Study (TACS).

The field notebook used to record observations and ideas as they occurred to the investigator, started as a 9 1/2-inch by 6-inch spiral notebook. Later, bound, numbered 8 1/2-inch by 11-inch record books were used. Four of these bound volumes were used in addition to the spiral notebook. The information recorded was anecdotal in nature, always attempting to capture diagrams that were drawn on whiteboard to supplement the verbal record provided by the transcripts.
Paradigm description

Because of the constraint relating to doing the knowledge acquisition work in the natural work setting, and the lack of information revealed through the literature review, the general methodology most suited to the task was that growing out of the naturalistic paradigm. A brief review of the paradigm, as espoused by Schwartz and Ogilvy (1979) was condensed from Lincoln and Guba, (1985), for review here. In the original, the positivistic and naturalistic approaches were compared/contrasted; here, only the naturalistic approach will be described. The review will include the axioms of the naturalistic approach, and their implications for research.

Lincoln and Guba (1985) and Kirk and Miller (1986) have described an approach that generates reliability and validity tests for the naturalistic approach. Since the present research has the nature of an extended, augmented case study pursued in a naturalistic setting and it was desirable to be able to make the strongest statements possible with respect to the research, the investigator chose adherence to the paradigm which reflected the nature of the study most closely, provided the best fit to the data collected and to the nature of the explanations generated. Additionally, the number of subjects available for the group design work mitigated against being able to make strong statements via the use of parametric or non-parametric statistical techniques.
Axioms of the Naturalistic Approach

The axioms of the naturalistic approach as described by Lincoln and Guba (1985), along with a short explanation of each follow. The first axiom concerns the nature of reality, holding that realities are multiple, constructed, and holistic (not fragmentable). The second axiom is about the relationship of the knower to the known, and states that knower and known are interactive and inseparable, not independent and capable of objectivity. Axiom three, the possibility of generalization, claims that the aim of inquiry is to develop an idiographic (time and context bound) body of knowledge in the form of "working hypotheses" that describe the case under examination. The fourth axiom considers the possibility of causal linkages, saying that all entities are in a state of mutual simultaneous shaping so that it is impossible to distinguish causes from effects.

Finally, the fifth axiom concerns the role of values in inquiry, stating that inquiry is value-bound in at least five ways, expressed more completely as corollaries to axiom five: (1) "Inquiries are influenced by inquirer values as expressed in the choice of a problem, evaluand, or policy option, and in the framing, bounding, and focusing of that problem, evaluand, or policy option.; (2) Inquiry is influenced by the choice of the paradigm that guides the investigation into the problem.;
(3) Inquiry is influenced by the choice of the substantive theory utilized to guide the collection and analysis of data and in the interpretation of findings.; (4) Inquiry is influenced by the values that inhere in the context.; and (5) With respect to corollaries 1 through 4 above, inquiry is either value-resonant (reinforcing or congruent) or value-dissonant (conflicting). Problem, evaluand, or policy option, paradigm, theory, and context must exhibit congruence (value-resonance) if the inquiry is to produce meaningful results."

Characteristics of Naturalistic Inquiry

Lincoln and Guba (1985) go on to describe 14 characteristics of operational naturalistic inquiry, justifying these characteristics in two ways: (1) logical dependence on the axioms as stated above.; and (2) coherence and interdependence among the characteristics. As these are reviewed by this investigator, the congruence (or lack of congruence) of these characteristics with the present study will be stated. Characteristic number one is that the study was done in a natural setting because naturalistic ontology suggests that the focus of this study, i.e. the designers, cannot be understood in isolation from their workplace, nor can the design group be understood by the study of member designers only. This study was completed in the place of work of each of the subjects. All interviews were conducted in the
subjects' workplace, and all design integration meetings were held in the Flight Dynamics Laboratory.

The second characteristic is that the investigator uses himself as a primary data gathering instruments because it would be virtually impossible to devise a priori a nonhuman instrument with sufficient adaptability to adjust to the variety of circumstances encountered.

Characteristic three is the utilization of tacit knowledge because much of the interaction between the investigator and the subjects occur at this level. The importance of the rapport established with the designers and members of the design team was critical to the findings of this study. This rapport which facilitates tacit understanding was first described as the psychological contract between the knowledge engineer and the subject (McCracken, 1987b). Tacit knowledge is becoming recognized as a part of the context in which expert thinking occurs, and, as such, must be taken into account when building intelligent systems (Klein, 1990).

The fourth characteristic of the naturalistic paradigm is a preponderance of qualitative as compared to quantitative methods because they are more adaptable to dealing with multiple levels of reality (individual designer and design team) and are more sensitive and adaptable to the mutually shaping influences and patterns that may be encountered.
Characteristic five is referred to as purposive sampling (as compared to random or representative sampling), favored in the naturalistic paradigm because it increases the scope of data exposed and maximizes the investigator's ability to devise grounded theory that takes adequate account of local conditions, local mutual shapings, and local values (which increase the likelihood of transferability). Grounded theory, geographic constraints, availability of subjects, and economic constraints forced the choice of purposive sampling.

Characteristic six, inductive data analysis, is preferred over deductive analysis because it is more likely to describe the setting and make decisions about transferability to other settings easier.

The seventh characteristic is grounded theory (guiding substantive theory which emerges from the data), and is preferred because no a priori theory was found which could encompass the range of behavior likely to be encountered. No a priori theory was found in the literature review for this study which could explain the range of behavior encountered, even retrospectively.

Characteristic eight is that the design emerges because it is not possible to know enough ahead of time to devise the design adequately. In this study, for example, it was not possible to know what the structure and content of the follow-up interviews would be until the data from the preliminary interviews were analyzed. Also, the structure and content of
the integration meetings were unknown, therefore, the methods used to capture and analyze that data could not be completely specified a priori.

The ninth characteristic is the negotiation and interpretation of outcomes with the subjects from whom the data were drawn because it was their knowledge constructs the investigator sought to reconstruct.

The tenth characteristic is the case study reporting mode used for naturalistic studies because it is more adaptable to the multiple perspectives required for reporting data about a given site, and supporting transferability to other sites. The description of design provided by the present study was basically an extended case study at the level of both the individual designer and the design team, supplemented by data rate, frequency and other data where appropriate.

Idiographic interpretation (in terms of the particulars of the case), including the drawing of conclusions, as compared to nomothetically (in terms of lawlike generalizations) is characteristic 11 and is preferred because of the possibility of different interpretations for different contexts and because interpretations depend heavily on local particulars for their validity.

Characteristic 12 is the tentative (as in hesitant) application of the broad application of the findings because of the differences in interactions which may occur from site to site, and in the particulars of the context. The
particular findings of this study can be assumed to hold only at the site, and in the context of the designers who composed the design group at the time of the study, and is reported as such.

Characteristic 13 is focus determined boundaries. This allows boundaries on the inquiry to be set by the emergent focus (problems for research) because that allows the focus to be set by the findings rather than preconceptions of the investigator. The shift from an initial focus on questions leading to information seeking to questions involved in structuring ill-defined problem space led to the use of question concept maps as a tool to organize and describe these findings.

Finally, characteristic 14, is the special criteria for trustworthiness as compared to conventional internal and external validity, reliability and objectivity. Substitute criteria called credibility, transferability, dependability, and confirmability along with empirical procedures are proposed which are claimed to adequately affirm the trustworthiness of the naturalistic approach. These criteria will be dealt with in Chapter IV, Data Analysis and Findings. These substitute criteria were needed because there was no way, a priori, to test the assumptions of parametric statistics, such as the assumption of a normal distribution, prior to their use. It also was not possible to show independence of the observer, stability over time and context,
and direct and unidirectional causality, therefore, adherence to and explanation within, the naturalistic paradigm. An overview of the methodology is presented next, followed by an expanded explanation of each step.

**Instruments**

A subject authorization document (Appendix A), and subject profile form (Appendix B) were prepared. A context description was created (Appendix D).

Question schedules were generated for the exploratory (Appendix E), introductory (Appendix F), preliminary (Appendix I), and follow-up interviews (Appendix L). Design diary instructions were generated (Appendix J).

An outline (Appendix G) and script (Appendix H) of the group presentation were prepared. Analysis sheets categories were selected and analysis sheets prepared (Appendix K), and a glossary explaining the meaning of categories (Appendix M) was created.

**Procedures**

Based on the literature review and discussions with research and development personnel of the company creating the blueprint for the intelligent design information support system a preliminary set of methods for knowledge acquisition was presented. These included: preliminary interviews, preliminary analysis sheets for interview questions, having
designers keep a diary of questions asked and information sought, the observation of and participation in integration meetings, and using concept mapping of questions as a communication tool.

The chronological order of the employment of the knowledge acquisition methods was as follows: (1) exploratory interviews; (2) introductory interviews; (3) group presentation; (3) preliminary interviews; (4) begin participation in and observation of design team meetings; (4) follow-up interviews; (5) continuing participation in and observation of design team meetings; (6) third interview; (7) concept mapping exercise with designers; (8) feedback from support system developers as to the effectiveness of concept maps as communication support devices; and (9) follow-up interview on level of questions.

The analytical techniques initially proposed included subject categorization of the questions extracted from the interviews, and connection to/evaluation with respect to information seeking behaviors and problem solving, summary description and statistical analysis of the categorization data, summary and analysis of design diary data in a similar manner to the interview data (which would permit a comparison of those two techniques as data acquisition methods appropriate to individual designer behavior). Interaction analysis was proposed to search for question patterns in the integration meeting data which would be used as descriptions
of problem-solving strategies and other cognitive structures. Error analysis was proposed to identify possible points of effort in design support system development.

The completed final set of methods was proposed in order to generate an integrated set of data from a variety of sources, paralleling the Halpern Audit Trail process for descriptive research in "naturalistic settings" as described in Lincoln and Guba (1985). The methodology as used in the study is described next.

**Exploratory Interviews (#1)**

Exploratory meetings were held with three key design personnel (with an average 25 years experience) to gain the confidence of those who were in a position to make the decision to allow the investigator to observe the designers/design team, begin acquisition of contextually relevant documents (to the design process as practiced on-site), and explore the possible execution of the initial data collection concepts. Questions were prepared to explore the issues the investigator felt were relevant to the study of crew system design, but the interview was relatively unstructured. See Appendix E for these questions.

Meetings were audiotaped, transcribed, and reviewed for content. They also provided evidence of the willingness of the subject population to participate in the study as well as a preliminary orientation to the specifics of the design
domain under scrutiny. As a result of the exploratory meetings a set of tentative methods was proposed. Documents acquired included journal articles, technical reports, papers presented at professional meetings, and internal memos and reports. These documents, as well as documents produced by the group during the course of the study, were reviewed and compiled into a design document notebook (the ring binders mentioned above), and were used as a reference by the investigator for the interpretation of interview data and meeting transcripts.

Introductory Interviews (#2)

Three introductory interviews were conducted with the same design personnel as in the exploratory interviews in order to: (1) gain a basic understanding of the nature of the crew system design job; (2) get a preliminary reaction to the basic concepts of the proposed data acquisition approach; (3) develop rapport with persons instrumental in getting approval for doing the work; and (4) probe for ways of modifying the prototype acquisition materials. A schedule of questions was prepared for each of these, and an agenda of topics to be discussed, but the format was again unstructured (See Appendix F). These meetings were audiotaped, transcribed, and reviewed for content. They also provided feedback for the modification of the proposed methods. Findings were used to modify
preliminary thoughts about the methodology, and modify prototype materials.

Preliminary Interview Practice and Refinement

Once the tentative interview schedule was created, the investigator planned an evaluation test run. The interview technique was practiced on two experienced designers (both Ph.D.s with an interest in the study of design, but not included in the subject population), working on delivery, question content, timing, notetaking, emphasis and follow-up questioning. These meetings were audiotaped, transcribed, and reviewed for content. They also provided feedback for the modification of the interview technique. Comments were solicited from the two subjects for suggestions to improve the interview technique.

Preliminary Interviews (#3)

The purpose of the preliminary interviews was to establish a baseline for the inquiry behavior of subjects, to review the data collection procedures, to distribute and explain the design diary, and to explain the analysis sheets. Establishing a psychological contract with the subjects was a part of the activity. This was done to get optimal subject participation in all methods of data collection.

An interview schedule was prepared in which the basic approach was to have the investigator lead the designer
through the decomposition of their job, from the level of
design projects, to the problems which the project addressed,
to the subproblems within the project on which they personally
worked, to the questions they believed they asked in solving
the problems, and the information they believed they sought in
response to those questions. See Appendix I for the question
schedule. The questions thus went from the broadest and most
open-ended questions at each level examined, to the most
specific with respect to the unit of analysis - the question
and the document or other unit of information. This was done
to avoid, as much as possible, leading the designer. Within
each level of analysis (problem and sub-problem) - the same
pattern was followed, i.e. from the most open to the most
closed interview questions.

Each preliminary interview lasted approximately one hour.
All interviews were audiotaped, with the investigator taking
notes on the questionnaire outline as the interview
progressed, and using these notes for reference to generate
the follow-up questions during the interview. Each tape was
dated, numbered and coded by subject number, transcribed and
edited. Approximately four to five hours of processing were
required for each hour of tape generated. The verbalized
questions were then extracted into a question set for each
designer interviewed. The understanding of the subject
designers gained in the preliminary interviews was used to
screen which would be most suitable to select for the observation techniques.

Design Diaries

The purpose of the design diary was to record in as natural a setting as possible, data about problems, questions asked, information sought and solutions generated during the design process. Design diary instructions were created, including the preparation of a glossary, and a three-by-five-inch spiral bound notebook with an example entry providing the structure for entries into the diary (See Appendix J).

The designers were asked to keep a diary of their daily inquiry behavior in a three-by-five-inch spiral bound notebook. This size was chosen to make it possible for the designers to keep the notebook in a shirt pocket. Brevity was stressed. The investigator did not want the designer to feel burdened by the diary. It was simply a tool to record question asking behaviors as they occurred, providing information that would be useful in filling out the analysis sheets for the diary data. If there were interesting insights the designer felt he could provide, they were instructed to feel free to use the diary to record them. They were asked to keep the diary with them during their daily schedule, recording any questions they were trying to answer - whether they led to information seeking behavior or not, as long as they pertained to their job, whether they were technical,
organizational, or other questions. The designers were asked to record who they talked to or where they went to seek information to answer the question, and some note about how long they spent in that information seeking activity. If they believed information was available about the question, but were unable to find it where they thought, they were asked to record their conjecture about where they thought they could find the information. The designers were asked to keep in mind that information sought implies a question, and to record those information seeking events in the form of questions. Finally, they were asked to record the source from which they finally received the answer to their question. They were asked to record one question-asking behavior to a page and to date each entry.

Interview Question Analysis Sheets

The interview questions were analyzed by the subjects using a set of categories prepared by the investigator, based on the literature review and exploratory and introductory interviews, of various aspects of the question asking, information seeking and problem-solving behaviors. Kerlinger (1973) said "The first step in any analysis is categorization." Kerlinger provided a set of five rules for partitioning sets of objects into categories. They were: (1) Categories should be set up according to the research problem and purpose.; (2) The categories should be exhaustive.; (3)
The categories should be mutually exclusive and independent.; (4) Each category (variable) should be derived from one classification principle.; and (5) Any categorization scheme must be on one level of discourse.

An attempt was made to follow this advice in the generation of the analysis sheets. Appendix K contains a copy of the analysis sheets. An analysis sheet glossary was prepared (Appendix M) to support the designers in their category selections.

Question Categories

"The prime requisite for a set of question categories is that the categories relate closely to the purposes of the question." (Hyman, 1979). These categories must be reliable and easy to use. Given a set of questions, it should be easy to classify them into the various categories more or less unambiguously. These categories should be able to be used by other classifiers. One of the goals of the analysis sheet work done by the designers was for the investigator to follow up on the interview process to get feedback on the appropriateness of the categories.

In examining questions as key elements within the design process, and as a means of achieving design goals, the investigator formulated a set of categories to classify problems, questions, and information sought, as well as their context(s). This set of categories allowed examination of the
similarities, differences, and patterns among questions and information types. Categories were selected based on a review of the literature for questions asked, information sought, and problem type in order to provide the subjects with analysis sheets for self-categorization of the questions from the interview process.

The categories had to be compatible with the knowledge representation utilized by the designer. Essential to the selection of the question categorization scheme was: (1) The questions were classified in terms of the response (information) sought.; (2) The information was viewed as factual (true).; and (3) There was no hierarchy between categories. This follows the scheme of Wilson (1953).

Information Categories

Categories of information sources and information receiving behavior were organized after the technique used by Kasperson (1978). He organized/classified as follows: (1) exposure - frequency of use of a communication channel, breadth or scope of exposure, all with reference to the designer's field of specialization; (2) evaluation - utility as reported by the designer; and (3) access - technique used to reach the source and the information. Channels were categorized as published vs personal and broken into types. Types of published sources were books, periodicals of original
research, reviews, etc. Interpersonal channels were peers, subordinates, experts, etc.

Problem Categories

Cody (1987) provided a set of categories for the classification of the topic of problem within which the questions were generated and the information was sought. This was modified by retaining only high level categories from that classification scheme. Those categories included: (1) crew system configuration; (2) displays and controls; (3) cost-effectiveness; (4) life support systems; and (5) operator performance.

Design goal categories were taken from Mostow (1985). Functionality, performance, and design process goals were seen as a part of the context for the activity of the support pursuing knowledge goals.

Group Presentation Preparation

The purpose of the group presentation was to present subjects with the reason for the data collection, the types of data to be collected, and the expected value to the participants. Data collection techniques and the expected time burden on the individual was also explained. A group presentation was prepared in which had as its goals: (1) an overview briefing of the methods of the study; (2) introduction to the specific; and (3) allaying fears of a
proprietary nature. See Appendices G and H for an outline and prepared script of the presentation, respectively. This presentation was given on November 11, 1987. The script was practiced for the presentation, but was not read to the subjects.

Personal Participation in Design Problem

The investigator took part in the group process by being assigned a task that was a part of the work in progress. The task was to prioritize formats for breakdown default presentation. Formats are mixed graphic/alphanumeric presentations of information from/about the aircraft and/or the outside world. The question of interest was "If a system failure occurs, what format that is currently being displayed can be overwritten with the system failure format?"

Integration Meeting Observations

The purpose of the observation of the integration meetings was to observe group design work in a live setting to gather transcripts of and make observations on the group problem-solving process. The integration meetings lasted approximately one hour to one and one-half hours each. All integration meetings were audiotaped, with the investigator taking notes during the meetings. Each tape was dated, numbered and coded by subject number, transcribed and edited.
A transcriber's document aid was created which listed terminology peculiar to the domain of crew system design to aid in the recognition of words with which the transcriber was unfamiliar (See Appendix P). This document was kept current for the duration of observation of the integration meetings.

An observer debriefing document was created which contained debriefing questions to aid the investigator in capturing as complete a set of written meeting observations as possible. The questions were marked on the transcript for each meeting, and extracted into the subject question set.

Follow-up Interviews (#4)

The purpose of the follow-up interviews were to focus on specific items identified in reviewing the transcripts of the preliminary interviews. An agenda of interview questions was created for each individual for the follow-up interviews. (See Appendix L). Items of interest were defined by reviewing the transcripts of the preliminary interviews and as a result of interaction with the designers outside the interview. Each of the follow-up interviews lasted approximately one-half hour. All interviews were audiotaped with the investigator taking notes on the questionnaire outline as the interview progressed. Each tape was dated, numbered and coded by subject number, transcribed and edited. The questions were then extracted into a question set for each designer interviewed.
Interview #5

The fifth set of interviews occurred after approximately six months of integration meeting observation and covered topics which arose because of observation and interaction with the designers. Question preparation involved reviewing the field notes and tentative ideas about the design process gleaned from the integration meeting transcripts. Each of these interviews lasted approximately one-half to one hour. All interviews were audiotaped using a Lanier microcassette recorder, with the investigator taking notes on the questionnaire outline as the interview progressed. Each tape was dated, numbered and coded by subject number, transcribed and edited. Approximately four to five hours of processing were required for each hour of tape generated. The questions were then extracted into a question set for each designer interviewed.

Interview #6

A sixth and final interview was conducted with the members of the design group as an exit review of the understanding the investigator had of design.

Level of Question Follow-up Interview

Following discovery of the level of question concept during the data analysis, a follow-up interview to further
explore this was necessary. An open question approach was used to avoid leading the subject.

Qualitative Analytic Methods

Interaction Analysis

Interaction analysis was applied to the transcripts of the interviews and integration meetings. Categorization was done for the interview transcripts. No sequence analysis was done. Four passes were required through the meeting transcripts to complete the interaction analysis. The first pass was to edit the transcript and insert subject identifiers by reviewing the hard copy and listening to the tape from which it originated. The second pass was used to mark implicit and explicit questions, and to familiarize the investigator with the subject matter in a more connected way than was possible when editing. Categories of question types were tentatively generated with respect to the problem-solving behavior of the group. The third pass segmented the conversation into clusters of questions and other statements on related topics. The fourth pass examined clusters for patterns of question asking behavior and errorful behavior. This technique of understanding the origin of errors and developing methods for reducing errors through support system design is advocated by Lewis and Norman (1986).
Notes were recorded directly on the transcripts themselves, and were reviewed periodically as the investigator gained more knowledge of the domain and the design process.

**Question Concept Mapping**

The technique of question concept mapping was used to provide a set of external concrete referents with which to communicate the understanding of design knowledge structures with the personnel on the design team, and to support communication of that knowledge to support system developers. Questions were extracted from the interview transcripts by subject, printed out, and cut apart such that one question occurred on a single sheet of paper.

The investigator then scheduled appointments with two designers on an individual basis for the purpose of creating question concept maps. First, the subjects were presented with an example concept map, and the procedure for doing concept mapping was explained as well as the use of concept mapping in the current study.

The extracted interview questions were then presented (in a randomized way) to the originators of the questions. The subject was asked to collect together in sets, those questions which they felt "hung together" in some fashion. The investigator chose one set for further work. When the set of questions chosen by the investigator was spread out in front
of the designer on an 11 by 17 inch sheet of paper (or more, taped together, if required), the subject was asked to sort questions which belonged to subsets of the chosen set of questions. These were taped down and circled to indicate membership in the set, and the subject was asked to generate a label for each subset. Next, relations were drawn between/among the subsets. These relations could be one or two way relations. Next, the designers were asked to label the relations. Finally, the overall set was named. Sample concept maps, exactly as created, are presented in Appendix T.

This structure was then the subject of discussion between the investigator and the subject, with a goal of understanding exactly what was or was not captured by the structural representation.

These concept maps were then discussed with support system developers who had experience not only in the design and development of information support systems, but also in the generation of systems specified by the design team.

Confirmation with System Developers

The question concept maps generated by the interaction of the investigator and the designers were taken to experienced computer information system developers, and to the software support team within the laboratory. They were used as a focal point for discussions about information system development using the question concept maps as a communication tool. The
system developers were then asked to respond anonymously to a questionnaire in which they were asked to rate various aspects of question concept mapping as a communication tool for use in information system development.

Quantitative Analytic Methods

Counts and Rates

Counts of questions in the interviews, diaries, and integration meetings were generated. These were broken down as: (1) total number of questions acquired; (2) total interview questions; (3) total integration meeting questions; and (4) total diary questions.

Rates of question-asking were generated for each of the knowledge acquisition methods. The total running time of each tape was recorded for both interviews and design team meetings. The number of questions was divided by the time of the tape.

The total number of different information sources read regularly by members of the design team was done, generated by manual count from the personal profile sheets.

Statistical Analysis

Summary, frequency and percentage data sheets were created from the interview analysis sheets completed by the design team members. Data files were generated as ASCII text
files. Raw data summed over row and column, along with percentages were reported.

The interview analysis sheet data were subjected to correlation analysis, row by column.

Chi-square statistics were computed on the interview analysis sheet data using the SPSS crosstabs procedure.

**Summary**

The proposed set of methodologies was first set forth in McCracken (1987b). This methodology can be applied to knowledge acquisition where expertise is distributed over a number of individuals, as compared to techniques where expertise is monolithic - concentrated in one individual, while providing insight into individual differences in problem solving and information seeking behavior. Chapter IV reports the results of the data analysis.
CHAPTER IV
RESULTS

Introduction

In this chapter, the results are organized in terms of the framework first presented in Chapter I. Problems and subproblems are restated, data relating to each is presented and each is discussed with respect to the implications for the structure of a support system for crew system designers.

One major theme of this chapter is identification of the need for two classes of support, one for conceptual design development, the other for concept instantiation (production and use of the simulator).

The second major theme of the chapter is the understanding of the structure internal to those classes of support. The importance of the distinction is that different types of questions require different types of support. It is proposed, and supported from the data, that question asking support is needed for the higher level conceptual development questions. Support for lower level questions is seen as more conventional database type information access.
Discussion of the results compares findings from the methods for knowledge acquisition, providing confirmation of the results from individual methods.

The correlation data reported are discussed at the significances of .10 or greater. All correlations which were prepared are reported, and these are interpreted as support for observations made on the raw data, and as support for observed trends. The correlation data is not intended to stand by itself, hence the choice of levels of significance.

Data and Results of Analyses with Respect to Problem Statements

Problem 1 - What is the appropriate structure for an information support system for the target population?

Subproblem 1 Can question asking behaviors of the subject population be identified which provide insight as to requirements for support system development?

Introduction

The data examined with respect to this subproblem included the design dimension, design phase, question goal, question type, and knowledge type category data from the interview analysis sheets. These data were generated from the preliminary interview analysis sheets in which the seven members of the design team classified each question they
reported in the interview that they asked during the design process. These classifications were non-exclusive, that is, a single question could belong to more than one category. The results are discussed below, with respect to Subproblem 1.

Design Dimension Categories

The set of categories grouped under design dimension was generated after an examination of the textual material gathered from the senior designers in the exploratory and introductory interviews. These were thus expected to correspond well to the structure of the design problem being worked and to be well suited to the terminology with which the design team was familiar. In order to ensure that the categories were responded to in as uniform a manner possible, definitions were generated when it was thought necessary for clarification and provided to the designers for reference while responding to the analysis sheets. See Appendix M for the definitions, and Appendix N for the set of questions.

Definitions and designers' questions are presented to provide examples of important categories. Functionality was defined as "fulfilling the stipulated needs". Questions included: (1) "What are the functions needed to accomplish this (mission) scenario?"; (2) "How will the function get accomplished?"; and (3) "What areas should technologies like voice control be applied versus is HOTAS - hands on throttle and stick - a better application for this function?"
Performance was defined as "efficiency or effectiveness of the components; a measure of the ability of a system to perform its functions". Questions included: (1) "How crews reacted to electronic countermeasures?"; (2) "If they (ground crews) performed better with early warning information versus not having that?"; and (3) "How visibility affected performance?"

Interaction effects were defined as "problems dealing with the effects of competing aspects of the design process". Questions judged to belong to this category included: (1) "What tasks should be done by the machine and what tasks should be done by the human?"; (2) "What is the minimum update rate for LED displays under various vibratory conditions?"; and (3) "How much information can we expect the operator to digest at the given chunks of time?"

The definition provided for integration was "factors included in the resolution of tradeoff decisions in the design process; the process of combining software elements, hardware elements, or both into an overall crew system or subsystem". Questions included: (1) "If we give the pilot that function to perform, what (media) do we have available to enable him to do it?"; and (2) "How fast is that information updated in the computer and is that fast enough for the display to be readable or usable?"

Physical characteristics were defined as "the size, color, material makeup, or arrangement of the components of
the crew system". Questions included: (1) "Now are these dimensions the scope or is this the dimension of the box?"; (2) "What is the seat cover supposed to look like?"; and (3) "If 15 inches is allowed, (off the elbow for the stick) when I start running that seat up is it going to be in a bad position?" Questions in these categories comprised 72% of the questions with respect to design dimension. Appendix M contains definitions for the other categories.

Data

The category with the highest number of questions was functionality (148), the lowest was a tie between maintainability and other (5 each). The mean number of questions per category was 44.4. (See Table 1.)

Table 1. Number of Design Dimension Questions by Subject and Category.

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>SUBJECT NUMBER</th>
</tr>
</thead>
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<tr>
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<tr>
<td>functionality</td>
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<tr>
<td>performance</td>
<td>15 01 30 29 21 17 01</td>
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<tr>
<td>interaction effects</td>
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<tr>
<td>integration</td>
<td>02 12 20 12 07 06 04</td>
</tr>
<tr>
<td>physical character.</td>
<td>07 02 28 16 00 02 03</td>
</tr>
<tr>
<td>resources</td>
<td>03 00 27 05 01 01 01</td>
</tr>
<tr>
<td>design process</td>
<td>15 06 03 04 01 02 04</td>
</tr>
<tr>
<td>aesthetics</td>
<td>02 00 03 15 00 00 02</td>
</tr>
<tr>
<td>reliability</td>
<td>02 00 07 12 00 00 00</td>
</tr>
<tr>
<td>trainability</td>
<td>02 00 02 00 11 05 00</td>
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<td>organization</td>
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<td>maintainability</td>
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<td>other</td>
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<tr>
<td>Total</td>
<td>91 45 193 135 68 59 31</td>
</tr>
<tr>
<td>%</td>
<td>15 07 31 22 11 09 05</td>
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</table>
Table 2 presents the correlation table for design dimension.

Table 2. Correlations of Number of Design Dimension Questions by Subjects.

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</table>

Discussion

The number of questions categorized in the design dimension indicated that the design group was very concerned with aspects of design related to conceptual development. Conceptual development was defined as the set of subproblems within the design process which produce descriptions of the crew system of varying type (graphic or text) and various levels of detail. Functionality, performance, interaction effects, and integration accounted for 63% of the questions while representing only 4 of 14 categories. Production and use oriented aspects such as maintainability, trainability,
reliability and safety totaled only 9.5% of the questions while representing the same number of categories.

Production and use oriented aspects were defined as the set of subproblems within the design process which either produce the physical instantiation of the conceptual process or is related to the subsequent use of the artifact (simulator). Trainability was grouped in this set because in the context of this study, training issues are developed on an evaluation by evaluation basis. Each evaluation or experiment therefore has a set of stand alone training issues which are addressed with respect to the instantiated design and the needs of the particular evaluation.

More than 57% of the Spearman correlations were significant at .05 or better for the design dimension data (12 of 21). Seven more were significant at .10 or less for a total of 19 of 21 significant correlations. Members of the design team tended to ask similar types of questions with respect to this set of categories. This is important with respect to the design of a support system because it indicates that support tools can be generated which will provide support to more than one individual.

The conceptual design orientation of the group becomes even more apparent if the raw data for the categories of physical characteristics and resources are examined more closely. Subject number 2 asked 28 of 58 physical characteristics questions, and 27 of 38 questions about
resources. One implication for the design of a support system for this group is an emphasis on resources for the support of conceptual design. Another, interlocking implication is the nature of the support required. The conceptually oriented questions tended not to have answers which could be stated in terms of facts in a database, or dimensions from technical sheets, or even statements of safety standards. A support system to help identify the interacting issues that need to be addressed in terms of questions to be asked would help focus the designer on the relevant subspace within the problem domain. Personal observation and data indicated that there were enough questions which are generic to the design process for any crew system design problem, whether fighter, bomber, transport or other design, to justify the generation of a question asking guide.

Design Phase Categories

The set of categories grouped under design phase was generated from information from the documents provided by designers in the exploratory and introductory interviews, and from material reviewed in the literature review. The categories which comprised the set were constraint finding, problem formulation, answer formulation, learning, evaluation/judgement, information retrieval, analysis, synthesis, explanation, and information control. Some examples of questions follow. The complete set of questions
is available in Appendix N. Definitions for these categories were deemed to be unnecessary.

Constraint finding questions were: (1) "What would have happened if the threshold (for the voice system recognition) had been set tighter to see what would happen to the accuracy and the error rate?"; (2) "What are the space layouts and sizes?"; and (3) "What kind of interface do you have, is it an RS 232 bus?". Problem formulation questions were: (1) "What are the design issues that the manufacturers of the ATF (Advanced Tactical Fighter) will have to deal with?"; (2) "What is the scenario the system will perform in?"; and (3) "How is the system going to be employed?".

Some answer formulation questions were: (1) "If we have a visual display, what will the specific medium be (CRT, LED, LCD)?"; (2) "What are the mil standards for the stick?"; and (3) "Is this compatible for the system I am bringing in for the voice?". Learning questions included: (1) "What do the experts say about the scenario?"; (2) "What display devices are available?"; and (3) "What can the software people do?".

Evaluation/judgement question examples were: (1) "What is required to evaluate the cockpit?"; (2) Does it sound reasonable to have this (design) sitting in front of a pilot?"; and (3) "How closely do you want to place those pixels?".
Data

The raw and summary data for questions asked by subjects with respect to the phase of the design problem is presented in Table 3.

<table>
<thead>
<tr>
<th>CATEGORY</th>
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<th>3</th>
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<td>06</td>
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Table 3. Number of Design Phase Questions by Subject and Category
Table 4 presents the correlation results for design phase.

### Table 4. Correlations of Number of Design Phase Questions by Subjects.

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<th>S2</th>
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<th>S4</th>
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<td>SIG  .289</td>
<td>SIG  .089</td>
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<td>N( 10)</td>
<td>N( 10)</td>
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<td>SIG  .089</td>
<td>SIG  .055</td>
<td>SIG  .055</td>
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</table>

Discussion

The category with the largest number of questions was constraint finding (111), the low was information control (4). The average number of questions per category was 50. An unexpected finding, supported both by the data and the field notes was the relatively low number of questions related to information seeking, and the relatively high number for adding structure. The number of questions related to constraint finding was 111 and problem formulation was 81 for a total of 38% as compared to information retrieval (35) and information control (21) for 11%. In retrospect, this was reasonable.
Again, this design team worked in the area of conceptual design. By definition, the problems upon which they worked were ill-defined (had low structure). Problem solving strategies identified from the integration meeting transcripts (discussed later in this chapter) dealt largely with ways of adding structure to the problem space. The raw data from the analysis sheets supported this concept.

Table 4 shows that for design phase, there was only one correlation of 21 significant at .05, with four others at .10 or better. Although this is not much better than chance, four of seven negative correlations found were for subject three. This subject had a large majority of questions oriented to the building of the simulator, hence many questions about hardware specification. This trend will be seen to continue in examination of subsequent data. This indicates that the methods employed can identify not only similarities in questions asked, but also discriminate differences in such behavior.

Information Goal Categories

Verification was defined as seeking information leading to confirmation of something already known, usually to increase confidence in the accuracy or truth of something already known. Questions included: (1) "Is our (designers') understanding of what you are going to do with the airplane accurate?"; (2) "Is the scenario accurate?"; and (3) "Are
these the dimensions of the scope or the dimensions of the box?". Clarification was defined as seeking information leading to reduction of confusion about an issue. Questions included: (1) "What information do I have to have to answer these questions?"; (2) "Could I get the information from the SPOs and ASD/EN?"; (3) "What information could I get?"; (4) "Can we get hold of it?"; and (4) "Can we get a briefing on it?"

Acquisition was defined as seeking knowledge previously not known; gaining new perspectives on a problem situation. Questions included: (1) "What algorithms are available to compute information we want to have (displayed in the cockpit)?"; (2) "Find out how someone else does it (voice in the cockpit)?"; and (3) "How was it done before?".

Data

In the information goal category set, a fairly even distribution of questions over categories was found. (See Table 5.) Acquisition was the most frequent category (191), "other" the least frequent (7) with a mean of 103 per category.
Table 5. Number of Information Goal Questions by Subject and Category.

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>SUBJECT NUMBER</th>
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<td>23</td>
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<td>07</td>
<td>191</td>
<td>46</td>
</tr>
<tr>
<td>clarification</td>
<td></td>
<td>11</td>
<td>07</td>
<td>43</td>
<td>28</td>
<td>07</td>
<td>12</td>
<td>15</td>
<td>123</td>
<td>30</td>
</tr>
<tr>
<td>verification</td>
<td></td>
<td>08</td>
<td>03</td>
<td>31</td>
<td>14</td>
<td>15</td>
<td>13</td>
<td>07</td>
<td>91</td>
<td>22</td>
</tr>
<tr>
<td>other</td>
<td></td>
<td>06</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>01</td>
<td>00</td>
<td>00</td>
<td>07</td>
<td>02</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>58</td>
<td>22</td>
<td>151</td>
<td>62</td>
<td>46</td>
<td>44</td>
<td>29</td>
<td>412</td>
<td></td>
</tr>
<tr>
<td>%</td>
<td></td>
<td>14</td>
<td>05</td>
<td>37</td>
<td>15</td>
<td>11</td>
<td>11</td>
<td>07</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6 presents the information goal correlation results.

Table 6. Correlations of Number of Information Goal Questions by Subjects.

<table>
<thead>
<tr>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
<td>0.8000</td>
<td>0.8000</td>
<td>0.8000</td>
</tr>
<tr>
<td>N(4)</td>
<td>N(4)</td>
<td>N(4)</td>
<td>N(4)</td>
<td>N(4)</td>
<td>N(4)</td>
</tr>
<tr>
<td>SIG .000</td>
<td>SIG .000</td>
<td>SIG .000</td>
<td>SIG .100</td>
<td>SIG .100</td>
<td>SIG .100</td>
</tr>
<tr>
<td>S7</td>
<td>S1</td>
<td>S2</td>
<td>S3</td>
<td>S4</td>
<td>S5</td>
</tr>
<tr>
<td>0.6325</td>
<td>0.6325</td>
<td>0.6325</td>
<td>.9487</td>
<td>.3162</td>
<td>.3162</td>
</tr>
<tr>
<td>N(4)</td>
<td>N(4)</td>
<td>N(4)</td>
<td>N(4)</td>
<td>N(4)</td>
<td>N(4)</td>
</tr>
<tr>
<td>SIG .184</td>
<td>SIG .184</td>
<td>SIG .184</td>
<td>SIG .026</td>
<td>SIG .342</td>
<td>SIG .342</td>
</tr>
</tbody>
</table>
Discussion

A large number of questions were used to acquire information. This supports the need for an information support for designers.

There was a higher number of significant correlations expected in the information goal category than was obtained (5 of 21 at .05 or less, with 9 more at .10 for a total of 14 of 21). The results were influenced by the very small number of categories. The data, however, indicates substantial similarity among the behaviors of the members of the design team.

Question Type Categories

"Why" questions were defined as asking about the purpose of an action or design choice. Questions included: (1) "Why not take out the middle phase (in a sequence if the computer can do it)?"; (2) "Why is the stick located there?"; and (3) "Why does the switch respond in that way?" "How" questions were those which asked about the way some goal of the design process was to be accomplished. Questions included: (1) "How do I get the shop to build given design to the specs?"; (2) "How would you hook up (the electronics)?"; and (3) "How much access do we have?".
Data

"How" questions occurred most frequently (130), finding component least frequently, with a mean of 62 questions per category. (See Table 7.)

Table 7. Number of Question Type Questions by Subject and Category.

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>SUBJECT</th>
<th>NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>how</td>
<td>32</td>
<td>16</td>
</tr>
<tr>
<td>why</td>
<td>14</td>
<td>01</td>
</tr>
<tr>
<td>yes/no</td>
<td>00</td>
<td>00</td>
</tr>
<tr>
<td>other</td>
<td>07</td>
<td>00</td>
</tr>
<tr>
<td>causal link</td>
<td>00</td>
<td>11</td>
</tr>
<tr>
<td>find component</td>
<td>00</td>
<td>01</td>
</tr>
<tr>
<td>Total</td>
<td>52</td>
<td>29</td>
</tr>
<tr>
<td>%</td>
<td>14</td>
<td>08</td>
</tr>
</tbody>
</table>

Table 8 presents correlation results for question type.

Table 8. Correlations of Number of Question Type Questions by Subjects.

| S2    | .3752 |
|       | N( 6) |
| SIG   | .232  |
| S3    | -.0308|
|       | N( 6) |
| SIG   | .477  |
| S4    | .6774 |
|       | N( 6) |
| SIG   | .070  |
| S5    | .5236 |
|       | N( 6) |
| SIG   | .143  |
| S6    | .6983 |
|       | N( 6) |
| SIG   | .061  |
| S7    | .0308 |
|       | N( 6) |
| SIG   | .477  |
| S1    | S2    |
| S3    | S4    |
| S5    | S6    |
Discussion

The even distribution of questions over categories found earlier for information goal also occurred for question type. The large number of questions categorized as other is problematic. This may have been remedied by adding more categories such as who, when, where, and what; however, the generic types of categories (those which do not correspond in some was to the design process) seemed to be adding little valuable insight into group similarities or differences. There may not be much payoff for work on this set.

The question type category set also yielded a small (4 of 21) number of correlations significant at the .05 level, and two more at .10. Again we see subject three with distinctively different behavior from the rest of the group, accounting for six of seven negative correlations.

Knowledge Type Categories

Semantic knowledge was defined as facts about the world; a question about a specific object or the value or some variable, either of which is perceived as having some objective reality. Questions included: (1) "What kind of stick is this?"; (2) "Is this analog?"; and (3) "Do I need lead for shielding?".

Explanative questions were defined as those which were directed at the clarification of the causes of some system behavior. Questions included: (1) "Once again, coming back to the checklist, if you have, if you are in an (other display),
the checklist, if you have, if you are in an (other display), what displays are going to disappear (to accommodate display of the checklist)?"; (2) "Do I have control over all the power in the room?"; and (3) "What words will you use to activate the switch?".

Procedural questions dealt with knowledge of how to perform a sequence of operations, such as the procedure for mission analysis. Examples included: (1) "What kind of (training) schedule will they go through?"; (2) "Is it necessary to use all three of those techniques to change a radar system or something like that?"; and (3) "(Out of two procedures to do things, how to tell) which way is better?". More definitions for this category may be found in Appendix K.

Data

The knowledge type question which occurred with most frequency was semantic (111), the least frequent was linguistic (40). The mean for all categories was 72. See Table 9.

Table 9. Number of Knowledge Type Questions by Subject and Category.

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>SUBJ 1</th>
<th>SUBJ 2</th>
<th>SUBJ 3</th>
<th>SUBJ 4</th>
<th>SUBJ 5</th>
<th>SUBJ 6</th>
<th>SUBJ 7</th>
<th>TOTAL</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>semantic</td>
<td>23</td>
<td>00</td>
<td>61</td>
<td>00</td>
<td>17</td>
<td>09</td>
<td>01</td>
<td>111</td>
<td>26</td>
</tr>
<tr>
<td>explanation</td>
<td>04</td>
<td>06</td>
<td>49</td>
<td>36</td>
<td>04</td>
<td>00</td>
<td>02</td>
<td>101</td>
<td>23</td>
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<td>procedural</td>
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<td>09</td>
<td>11</td>
<td>13</td>
<td>04</td>
<td>07</td>
<td>15</td>
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<td>17</td>
<td>18</td>
<td>08</td>
<td>59</td>
<td>14</td>
</tr>
<tr>
<td>strategic</td>
<td>08</td>
<td>00</td>
<td>11</td>
<td>27</td>
<td>04</td>
<td>06</td>
<td>01</td>
<td>57</td>
<td>13</td>
</tr>
<tr>
<td>linguistic</td>
<td>04</td>
<td>09</td>
<td>04</td>
<td>00</td>
<td>16</td>
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<td>40</td>
<td>09</td>
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<tr>
<td>Total</td>
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<td>76</td>
<td>62</td>
<td>45</td>
<td>29</td>
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<tr>
<td>%</td>
<td>12</td>
<td>07</td>
<td>33</td>
<td>18</td>
<td>14</td>
<td>10</td>
<td>07</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The correlation results for the knowledge type data are presented in Table 10.

Table 10. Correlations of Number of Knowledge Type Questions by Subjects.

<table>
<thead>
<tr>
<th></th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-.8508</td>
<td>.4412</td>
<td>-.2772</td>
<td>.4070</td>
<td>.6957</td>
<td>-.5075</td>
</tr>
<tr>
<td>N</td>
<td>(6)</td>
<td>(6)</td>
<td>(6)</td>
<td>(6)</td>
<td>(6)</td>
<td>(6)</td>
</tr>
<tr>
<td>SIG</td>
<td>.016</td>
<td>.191</td>
<td>.297</td>
<td>.212</td>
<td>.062</td>
<td>.152</td>
</tr>
</tbody>
</table>

Discussion

The generic (with respect to design) categorizations of linguistic, semantic, schematic, procedural, explanatory, and strategic categories yielded three correlations significant at .05 and three more at .10. Positive and negative correlations are distributed across subjects. While the correlations were high for several variables, the small n (6) required very high r's for significance. If the correlation pattern continued for larger samples, there may be more significant differences.
Subproblem 2  Can information seeking behaviors of the subject population be identified which provide insight as to requirements for support system development?

Introduction

The data presented to support conclusions for Subproblem 2 are derived from the information analysis sheet data generated by the subjects from the questions reported during the preliminary interviews. Some classifications were non-exclusive, that is, a single information item could belong to more than one category, while others, such as time to access, were mutually exclusive. Because the categories are self-explanatory, discussion of definitions will not be done. An examination of information characteristics with respect to question characteristics was not done, therefore, data will simply be presented and discussed.

Information Type Data

The type of information accessed in the raw data showed that the knowledge of other people (161) was the most frequent type of information accessed. The least frequent type of information category accessed (apart from the unspecified other) was books (6). The mean number of questions per
category was 56. (See Table 11.) The correlation results for the information type data are presented in Table 12.

Table 11. Number of Information Type Items by Subject and Category.

<table>
<thead>
<tr>
<th>SUBJECT NUMBER</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>Total</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>other person</td>
<td>09</td>
<td>00</td>
<td>43</td>
<td>29</td>
<td>29</td>
<td>10</td>
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<td>28</td>
</tr>
<tr>
<td>own knowledge</td>
<td>09</td>
<td>00</td>
<td>43</td>
<td>29</td>
<td>29</td>
<td>07</td>
<td>12</td>
<td>129</td>
<td>26</td>
</tr>
<tr>
<td>technical report</td>
<td>06</td>
<td>00</td>
<td>07</td>
<td>28</td>
<td>10</td>
<td>14</td>
<td>01</td>
<td>66</td>
<td>13</td>
</tr>
<tr>
<td>project document.</td>
<td>01</td>
<td>00</td>
<td>10</td>
<td>27</td>
<td>17</td>
<td>09</td>
<td>01</td>
<td>65</td>
<td>13</td>
</tr>
<tr>
<td>journal/periodical</td>
<td>07</td>
<td>03</td>
<td>01</td>
<td>28</td>
<td>00</td>
<td>12</td>
<td>05</td>
<td>56</td>
<td>11</td>
</tr>
<tr>
<td>statement of need</td>
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<td>11</td>
<td>02</td>
<td>00</td>
<td>00</td>
<td>02</td>
<td>00</td>
<td>26</td>
<td>05</td>
</tr>
<tr>
<td>design handbook</td>
<td>00</td>
<td>06</td>
<td>01</td>
<td>00</td>
<td>00</td>
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<td>01</td>
<td>06</td>
<td>01</td>
</tr>
<tr>
<td>other</td>
<td>00</td>
<td>00</td>
<td>02</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>02</td>
<td>00</td>
</tr>
<tr>
<td>Total</td>
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<td>20</td>
<td>109</td>
<td>141</td>
<td>85</td>
<td>57</td>
<td>45</td>
<td>505</td>
<td></td>
</tr>
<tr>
<td>%</td>
<td>10</td>
<td>04</td>
<td>22</td>
<td>28</td>
<td>17</td>
<td>11</td>
<td>09</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 12. Correlations of Number of Information Type Items by Subjects.

<table>
<thead>
<tr>
<th>S2</th>
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<th>SIG .308</th>
</tr>
</thead>
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<td>S3</td>
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<td>-.4563</td>
</tr>
<tr>
<td></td>
<td>N( 9)</td>
<td>SIG .143</td>
</tr>
<tr>
<td></td>
<td>N( 9)</td>
<td>SIG .109</td>
</tr>
<tr>
<td>S4</td>
<td>.5138</td>
<td>-.4123</td>
</tr>
<tr>
<td></td>
<td>N( 9)</td>
<td>SIG .079</td>
</tr>
<tr>
<td></td>
<td>N( 9)</td>
<td>SIG .135</td>
</tr>
<tr>
<td></td>
<td>SIG .013</td>
<td></td>
</tr>
<tr>
<td>S5</td>
<td>.3608</td>
<td>-.5887</td>
</tr>
<tr>
<td></td>
<td>N( 9)</td>
<td>SIG .170</td>
</tr>
<tr>
<td></td>
<td>N( 9)</td>
<td>SIG .048</td>
</tr>
<tr>
<td></td>
<td>N( 9)</td>
<td>SIG .000</td>
</tr>
<tr>
<td></td>
<td>SIG .003</td>
<td></td>
</tr>
<tr>
<td>S6</td>
<td>.1880</td>
<td>-.2115</td>
</tr>
<tr>
<td></td>
<td>N( 9)</td>
<td>SIG .314</td>
</tr>
<tr>
<td></td>
<td>N( 9)</td>
<td>SIG .292</td>
</tr>
<tr>
<td></td>
<td>N( 9)</td>
<td>SIG .146</td>
</tr>
<tr>
<td></td>
<td>SIG .009</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SIG .083</td>
<td></td>
</tr>
<tr>
<td>S7</td>
<td>.8756</td>
<td>-.0657</td>
</tr>
<tr>
<td></td>
<td>N( 9)</td>
<td>SIG .001</td>
</tr>
<tr>
<td></td>
<td>N( 9)</td>
<td>SIG .433</td>
</tr>
<tr>
<td></td>
<td>N( 9)</td>
<td>SIG .073</td>
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<tr>
<td></td>
<td>N( 9)</td>
<td>SIG .007</td>
</tr>
<tr>
<td></td>
<td>SIG .047</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SIG .144</td>
<td></td>
</tr>
</tbody>
</table>

S1  S2  S3  S4  S5  S6
Discussion

The correlation analysis of the data yielded seven comparisons significant at less than .05, with three more at .10, and four more at .15 or better. An examination of the raw data indicated that this was due to the use of human knowledge bases as the information source of choice. This similarity can be explained by an examination of the context in which the team operated. The team was charged with the development of concepts for aircraft scheduled to fly 10 to 20 years into the future. As such, it was not likely that "the book" would have been written on the design they were pursuing. Even relevant experimental work, reported in the academic/scholarly journals was not likely to be done in the same context (cockpit environment) as the design team member would apply the information. Another person, from whom the designer has sought information before, was more likely to be able to contextualize the information, thus enhancing its value.

Perhaps a common thread or dimension would be represented by a continuum from static information source (book) to fluid information source (own knowledge and other people). This would indicate that the state of the art in terms of information was held in fluid, easily updated databases, and were the most likely receptacle for information having the highest value for the designers.
Five negative correlations are present in Table 12. All five are recorded for subject five. Looking at the raw data, this subject sought no information from another person and never used his own knowledge. This subject had relatively little experience in doing crew system design, and probably few personal contacts were developed to provide information.

Document Length Information Data

Document length showed no apparent differences in the raw data. Documents 25-100 pages long were accessed most frequently, and 10-25 pages least frequently. The mean was 38 questions per category. (See Table 13.)

Table 13. Number of Document Length Items by Subject and Category.

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>SUBJECT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4 5 6 7</td>
</tr>
<tr>
<td>0-10 pages</td>
<td>17 00 06 05 00 06 01</td>
</tr>
<tr>
<td>10-25 pages</td>
<td>05 00 03 00 01 05 05</td>
</tr>
<tr>
<td>25-100 pages</td>
<td>00 05 05 14 12 10 04</td>
</tr>
<tr>
<td>100 or more pages</td>
<td>03 03 00 11 13 18 00</td>
</tr>
<tr>
<td>Total</td>
<td>25 08 14 30 26 39 10</td>
</tr>
<tr>
<td>%</td>
<td>16 05 09 20 17 26 07</td>
</tr>
</tbody>
</table>
The results of the correlation analysis of the raw data for document length is presented in Table 14.

Table 14. Correlations of Number of Document Length Items by Subjects.

<table>
<thead>
<tr>
<th></th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-.9487</td>
<td>.4000</td>
<td>-.8000</td>
<td>-.8000</td>
<td>-.6000</td>
<td>.0000</td>
</tr>
<tr>
<td>N(4)</td>
<td>SIG .026</td>
<td>SIG .395</td>
<td>SIG .100</td>
<td>SIG .026</td>
<td>SIG .500</td>
<td>SIG .131</td>
</tr>
<tr>
<td>SIG .9487</td>
<td>N(4)</td>
<td>N(4)</td>
<td>N(4)</td>
<td>N(4)</td>
<td>N(4)</td>
<td>N(4)</td>
</tr>
<tr>
<td>SIG .4000</td>
<td>SIG .395</td>
<td>SIG .100</td>
<td>SIG .131</td>
<td>SIG .300</td>
<td>SIG .100</td>
<td>SIG .131</td>
</tr>
</tbody>
</table>

Discussion

The lack of differences in the raw data was supported by the appearance of only two correlations significant at .05 or less in the length of document data, with six more at .10. The distribution of positive and negative correlations across subjects and the distribution of results in the raw data indicated that subjects did not care how long a document was in their choice of information source. It could be hypothesized that the only thing they cared about was getting the information they needed, not the length of the document.
from which it was accessed. Eight of eleven negative correlations were accounted for by subjects one and seven. It is not apparent to this investigator that this reflected any meaningful pattern.

Conversation Length Data

Conversation length data showed that the least frequent were short conversations of 0-5 minutes (10), and most were 10-30 minutes (68). (See Table 15.) The trend is in the direction of longer conversations.

Table 15. Number of Length of Conversation Items by Subject and Category.

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>SUBJECT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4 5 6 7 Total %</td>
</tr>
<tr>
<td>0-5 minutes</td>
<td>03 00 05 01 00 00 01 10  05</td>
</tr>
<tr>
<td>5-10 minutes</td>
<td>01 04 17 00 03 03 05 33  18</td>
</tr>
<tr>
<td>10-30 minutes</td>
<td>07 06 38 02 01 04 10 68  37</td>
</tr>
<tr>
<td>30 or more minutes</td>
<td>15 01 16 15 01 18 07 73  40</td>
</tr>
<tr>
<td>Total</td>
<td>26 11 76 18 05 25 23 184</td>
</tr>
<tr>
<td>%</td>
<td>14 06 41 10 03 14 13</td>
</tr>
</tbody>
</table>
The correlation results for the length of conversation data are presented in Table 16.

Table 16. Correlations of Number of Length of Conversation Items by Subjects.

<table>
<thead>
<tr>
<th></th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>.0000</td>
<td>.0000</td>
<td>1.0000</td>
<td>.0000</td>
<td>.0000</td>
<td>.0000</td>
</tr>
<tr>
<td>SIG</td>
<td>.500</td>
<td>.500</td>
<td>.500</td>
<td>.500</td>
<td>.500</td>
<td>.500</td>
</tr>
<tr>
<td>N</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Discussion

The raw data show that 77% of the information seeking conversations were of longer than 10 minutes duration. The correlation analysis for the length of conversation showed 2 of 21 were significant at .05 or less, with 4 more at .10 or less. It seemed that the complexity of the domain did not admit of simple answers, even to relatively simple questions. Subject 5 was the least experienced member of the team, while subject 2 was the next least experienced. This may explain
the low number of conversations for each of them, in that they may not have known whom to ask.

**Time to Access Information Data**

The time to access the information source showed an inverse relation to the frequency of access. The longer it took to access information, the fewer times it was accessed. Access times of 0-1/2 hour were most frequent (112), with the least 5 or more days (2). The mean per category was 43. See Table 17.

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>SUBJECT NUMBER</th>
<th>Total</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1   2   3   4   5   6   7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-1/2 hour</td>
<td>09  09  19  01  37  23  14</td>
<td>112</td>
<td>44</td>
</tr>
<tr>
<td>1/2-1 hour</td>
<td>02  04  43  05  06  05  10</td>
<td>75</td>
<td>29</td>
</tr>
<tr>
<td>1-4 hours</td>
<td>07  01  07  29  06  06  01</td>
<td>57</td>
<td>22</td>
</tr>
<tr>
<td>4-8 hours</td>
<td>01  00  01  01  01  00  00</td>
<td>04</td>
<td>2</td>
</tr>
<tr>
<td>1-5 days</td>
<td>06  00  01  00  00  00  00</td>
<td>07</td>
<td>3</td>
</tr>
<tr>
<td>over 5 days</td>
<td>02  00  00  00  00  00  00</td>
<td>02</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>27  14  71  36  50  34  25</td>
<td>257</td>
<td></td>
</tr>
<tr>
<td>%</td>
<td>11  05  28  14  19  13  10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The correlation results for the time to access data are presented in Table 18.

**Table 18. Correlations of Time to Access Information Items by Subjects.**

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>S2</td>
<td>.6160</td>
<td>N(6)</td>
<td>SIG .096</td>
<td></td>
</tr>
<tr>
<td>S3</td>
<td>.3824</td>
<td>.8933</td>
<td>N(6)</td>
<td>N(6) SIG .227 SIG .008</td>
</tr>
<tr>
<td>S4</td>
<td>.1941</td>
<td>.5940</td>
<td>.7165</td>
<td>N(6)</td>
</tr>
<tr>
<td>S5</td>
<td>.5374</td>
<td>.9380</td>
<td>.8508</td>
<td>.7273</td>
</tr>
<tr>
<td>S6</td>
<td>.7701</td>
<td>.9355</td>
<td>.7701</td>
<td>.6566</td>
</tr>
<tr>
<td>S7</td>
<td>.6160</td>
<td>1.0000</td>
<td>.8933</td>
<td>.5940</td>
</tr>
</tbody>
</table>

**Discussion**

The raw data seemed to provide evidence that parallels the findings of Allen (1977), Zipf (1949), and Boff (1987) indicating that the more effort or time required, the less likely it is that information will be accessed. Ninety-five percent of all access events were categorized as occurring under four hours. This finding, along with the type of information accessed (other person - contextualized information in rapidly updated knowledge base), is directly
parallel to Allen (1977). This information would be of highest possible value, and least cost.

The correlation results support the raw data. Eleven correlations are significant at .05 or less with five more at .10 or less. No negative correlations were found. The time pressure under which the team works lends itself to the need for rapid access to information. This becomes even more significant when this finding is reviewed in the light of length of document findings reported earlier. These two argue even more strongly for the need for computer based access to information.

Time to Evaluate Information Data

The findings for time to access seemed to hold for time to evaluate, though not to as great an extent. The number of items were most for evaluation times of 0-1/2 hour (79), least for 4-8 hours (9), and 8 or more hours (12). (See Table 19.)

Table 19. Number of Time to Evaluate Information Items by Subject and Category.

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>SUBJECT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4 5 6 7 Total %</td>
</tr>
<tr>
<td>0-1/2 hour</td>
<td>15 05 25 01 03 26 04 79 30</td>
</tr>
<tr>
<td>1/2-1 hour</td>
<td>02 10 44 04 11 10 07 88 33</td>
</tr>
<tr>
<td>1-4 hours</td>
<td>02 03 20 28 06 08 09 76 29</td>
</tr>
<tr>
<td>4-8 hours</td>
<td>00 00 04 00 00 00 05 09 03</td>
</tr>
<tr>
<td>over 8 hours</td>
<td>07 01 00 03 00 00 01 12 05</td>
</tr>
<tr>
<td>Total</td>
<td>26 19 93 36 20 44 26 264</td>
</tr>
<tr>
<td>%</td>
<td>10 07 35 14 08 17 10</td>
</tr>
</tbody>
</table>
The correlation results for the time to evaluate data are presented in Table 20.

**Table 20. Correlations of Number of Time to Evaluate Information Items by Subjects.**

<table>
<thead>
<tr>
<th>S2</th>
<th>N(5)</th>
<th>SIG .246</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3</td>
<td>N(5)</td>
<td>SIG .435</td>
</tr>
<tr>
<td></td>
<td>N(5)</td>
<td>SIG .019</td>
</tr>
<tr>
<td>S4</td>
<td>N(5)</td>
<td>SIG .467</td>
</tr>
<tr>
<td></td>
<td>N(5)</td>
<td>SIG .196</td>
</tr>
<tr>
<td></td>
<td>N(5)</td>
<td>SIG .312</td>
</tr>
<tr>
<td>S5</td>
<td>N(5)</td>
<td>SIG .050</td>
</tr>
<tr>
<td></td>
<td>N(5)</td>
<td>SIG .300</td>
</tr>
<tr>
<td></td>
<td>N(5)</td>
<td>SIG .435</td>
</tr>
<tr>
<td>S6</td>
<td>N(5)</td>
<td>SIG .500</td>
</tr>
<tr>
<td></td>
<td>N(5)</td>
<td>SIG .027</td>
</tr>
<tr>
<td></td>
<td>N(5)</td>
<td>SIG .086</td>
</tr>
<tr>
<td>S7</td>
<td>N(5)</td>
<td>SIG .181</td>
</tr>
<tr>
<td></td>
<td>N(5)</td>
<td>SIG .027</td>
</tr>
<tr>
<td></td>
<td>N(5)</td>
<td>SIG .370</td>
</tr>
<tr>
<td></td>
<td>N(5)</td>
<td>SIG .101</td>
</tr>
</tbody>
</table>

**Discussion**

It should be noted that in the category of 8 or more hours, subject 1 accounted for 7 of the 12 items. This was natural—subject 1 was the group leader, and responsible for the output of the group. It appeared that if a designer found an appropriate source of information, they invested time in evaluation. There was, however, still a trend toward fewer evaluations for longer time required.

The time to evaluate correlations were more equivocal. Only 5 of 21 correlations were significant at the .05 level,
and only 2 more at .10. Time to evaluate may have been a difficult category to estimate, in that there may have been confusion as to differences between leafing through, reading, absorbing and evaluating.

Subproblem 3  Can problem solving behaviors of the subject population be identified which provide insight as to requirements for support system development?

Introduction

The data presented for discussion with respect to Subproblem 3 were taken from the Problem Analysis Sheet. (See Appendix K.) These categorizations were generated by the designers based on the questions they reported asking in the preliminary interviews.

Problem Task Data

In examining the raw data from the problem task categories, they fell roughly into two major headings - conceptually oriented and production and use oriented. Those problem tasks related to conceptual development included: analyze operational requirements, define operational requirements, develop system performance criteria, develop system functional specifications, function analysis,
man-machine function allocation, and crew system interface analysis. Task analysis, error analysis, and crew system operating procedures design, this investigator included with production and use orientation, believing that these could not be accomplished until the cockpit was at least mocked up. Part-system mockup and simulation, crew system layout, instructional system development, engineering simulation, prototype development, detailed design, field testing, system production, and sustaining engineering were more straightforward in their production and use orientation. The total number of conceptual development questions was 378, while production and use was 316. Again, this reflects the partitioning seen in previous data sets.

What was even more salient was partialing out the questions of subject three, reinforcing differences found earlier with respect to question asking and information seeking behavior. The number of conceptual questions dropped to 369, while the production and use questions total dropped to 178. The number of questions for each of those categories is provided as subtotals in Table 21.
Table 21. Number of Problem Task Items by Subject and Category.

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>SUBJECT NUMBER</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>Total</td>
<td></td>
<td>%</td>
</tr>
<tr>
<td>Conceptual</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>analyze op. reqs.</td>
<td>17</td>
<td>06</td>
<td>00</td>
<td>18</td>
<td>13</td>
<td>07</td>
<td>06</td>
<td>67</td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>define op. reqs.</td>
<td>22</td>
<td>03</td>
<td>03</td>
<td>05</td>
<td>14</td>
<td>00</td>
<td>03</td>
<td>50</td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>dev. perf. crit.</td>
<td>19</td>
<td>00</td>
<td>02</td>
<td>29</td>
<td>00</td>
<td>08</td>
<td>10</td>
<td>68</td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>dev. func. spec.</td>
<td>14</td>
<td>01</td>
<td>02</td>
<td>11</td>
<td>00</td>
<td>12</td>
<td>04</td>
<td>44</td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>function anal.</td>
<td>08</td>
<td>01</td>
<td>00</td>
<td>15</td>
<td>00</td>
<td>00</td>
<td>08</td>
<td>32</td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>man-mch. fnc. al.</td>
<td>19</td>
<td>10</td>
<td>00</td>
<td>08</td>
<td>00</td>
<td>00</td>
<td>02</td>
<td>39</td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>crew sys. intrfce.</td>
<td>12</td>
<td>17</td>
<td>02</td>
<td>23</td>
<td>10</td>
<td>00</td>
<td>14</td>
<td>78</td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>378</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hardware</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>detailed design</td>
<td>08</td>
<td>00</td>
<td>57</td>
<td>04</td>
<td>00</td>
<td>00</td>
<td>02</td>
<td>71</td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>crew sys. op. proc.</td>
<td>07</td>
<td>05</td>
<td>05</td>
<td>12</td>
<td>15</td>
<td>10</td>
<td>03</td>
<td>57</td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>prototype develop.</td>
<td>07</td>
<td>01</td>
<td>32</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>40</td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>task analysis</td>
<td>09</td>
<td>00</td>
<td>00</td>
<td>15</td>
<td>00</td>
<td>00</td>
<td>05</td>
<td>29</td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>mockup/simulation</td>
<td>00</td>
<td>10</td>
<td>03</td>
<td>05</td>
<td>00</td>
<td>07</td>
<td>00</td>
<td>25</td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>crew system layout</td>
<td>08</td>
<td>07</td>
<td>05</td>
<td>05</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>25</td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>engineering simul.</td>
<td>00</td>
<td>00</td>
<td>25</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>25</td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>other</td>
<td>03</td>
<td>00</td>
<td>07</td>
<td>10</td>
<td>00</td>
<td>00</td>
<td>02</td>
<td>22</td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>error analysis</td>
<td>00</td>
<td>00</td>
<td>13</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>13</td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>sustain. engineer.</td>
<td>02</td>
<td>00</td>
<td>02</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>04</td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>instruct. sys. dev.</td>
<td>00</td>
<td>00</td>
<td>02</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>01</td>
<td>03</td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>field testing</td>
<td>02</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>02</td>
<td>02</td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>system production</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td>00</td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>316</strong></td>
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<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>694</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>%</td>
<td>23</td>
<td>09</td>
<td>21</td>
<td>25</td>
<td>07</td>
<td>06</td>
<td>09</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The correlation results for the problem task data for conceptual categories are presented in Table 22.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Correlation (r)</th>
<th>N(20)</th>
<th>SIG</th>
<th>N(20)</th>
<th>SIG</th>
<th>N(20)</th>
<th>SIG</th>
<th>N(20)</th>
<th>SIG</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2</td>
<td>.4352</td>
<td>20</td>
<td>.028</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S3</td>
<td>-.1014</td>
<td>20</td>
<td>.335</td>
<td></td>
<td></td>
<td>.0319</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S4</td>
<td>.5858</td>
<td>20</td>
<td>.003</td>
<td>.3303</td>
<td>.082</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S5</td>
<td>.4091</td>
<td>20</td>
<td>.037</td>
<td>.5102</td>
<td>.415</td>
<td>.0510</td>
<td>.056</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S6</td>
<td>.2527</td>
<td>20</td>
<td>.141</td>
<td>.2800</td>
<td>.452</td>
<td>.0290</td>
<td>.029</td>
<td>.4307</td>
<td>.3034</td>
</tr>
<tr>
<td>S7</td>
<td>.7447</td>
<td>20</td>
<td>.000</td>
<td>.2642</td>
<td>.184</td>
<td>-.2126</td>
<td>.130</td>
<td>.8160</td>
<td>.3608</td>
</tr>
</tbody>
</table>

Discussion

The problem solving task data show 8 of 21 correlations significant at the .05. This again was without partialing out the data for the subject who worked directly on the cockpit as was done for the raw data. An additional 5 correlations existed of .10 or less. When examining negative correlations, all three belong to subject three, and the r values for each of the positive comparisons for subject 3 are low. We now have differences between subject three and the group across
the spectrum of question asking, information seeking and problem solving categories.

Problem Topic Data

With respect to questions relating to problem topic, the emphasis is still on a pre-production crew system design. Crew system configuration, displays and controls, and operator performance were issues strongly relating to a TACS type crew system, while cost-effectiveness and life support were not strongly related. The highest frequency category was displays and controls (167); the lowest was cost effectiveness (7). The mean was 69. (See Table 23.)

Table 23. Number of Problem Topic Items by Subject and Category.

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>SUBJECT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>displays/controls</td>
<td>28</td>
</tr>
<tr>
<td>crew sys. config.</td>
<td>27</td>
</tr>
<tr>
<td>operator perform.</td>
<td>05</td>
</tr>
<tr>
<td>other</td>
<td>11</td>
</tr>
<tr>
<td>life support</td>
<td>03</td>
</tr>
<tr>
<td>cost effectiveness</td>
<td>03</td>
</tr>
<tr>
<td>Total</td>
<td>77</td>
</tr>
<tr>
<td>%</td>
<td>19</td>
</tr>
</tbody>
</table>
The correlation results for the problem topic data are presented in Table 24.

### Table 24. Correlations of Number of Problem Topic Items by Subjects.

<table>
<thead>
<tr>
<th></th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SIG .020</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>.8317</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N( 6)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIG .020</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>.7247</td>
<td>.2732</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SIG .110</td>
<td>SIG .020</td>
<td>SIG .457</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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<td>SIG .000</td>
<td>SIG .300</td>
<td>SIG .020</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>.5145</td>
<td>.7184</td>
<td>.1014</td>
<td>.8232</td>
<td>.7184</td>
<td></td>
<td></td>
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<tr>
<td>SIG .148</td>
<td>SIG .054</td>
<td>SIG .424</td>
<td>SIG .022</td>
<td>SIG .054</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>.9549</td>
<td>.7419</td>
<td>.7590</td>
<td>.4004</td>
<td>.7419</td>
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</tr>
<tr>
<td>SIG .002</td>
<td>SIG .046</td>
<td>SIG .040</td>
<td>SIG .216</td>
<td>SIG .046</td>
<td>SIG .242</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Discussion

Eight of 21 correlations for the problem topic showed probabilities of .05 or better; three others were .10 or less. The similarities among members of the group continues, while subject three is involved in the only negative correlation. Perhaps the most important result for the problem topic categorization scheme is the large number of items in the other category. This indicates the need for additional categories or better resolution in terms of numbers of levels of the present categories.
Subproblem 4 Can priorities for development of the support system be generated by identifying errors in design problem solving?

Introduction

The data examined for discussion with respect to this subproblem were the transcripts of the integration meetings. Self-report data such as the interview material was deemed to be unreliable for these purposes.

Discussion

Errors committed in the prosecution of design related mostly to the overload of short term memory. The number of variables involved was so large, and the structure in which they were embedded so complex, that even very conscientious, intelligent designers made errors. These errors consisted of forgetting the local context with respect to the hierarchical decomposition of functions. The best example of this was losing track of which sub-heading was the current one while doing function analysis. See Appendix Y for a copy of the function analysis.

These errors occurred within the hierarchy when the design team reached a decomposition level three or more levels removed from the top level at which they were working. This did not seem to be related to the structure of problem
solving, but rather to the limits on short term memory. Johnson (1985) has suggested that in complex domains (of which this investigator will claim crew system design is an example), that Miller's (1956) magic number 7 +/- 2 should be more like 5 +/- 2.

That would indicate that the position at which errors occurred was the point at which the burden on short term memory was great enough to force the top level category descriptors out of the queue. Loss of this top level descriptor as the context in which the design team was thinking about the current item of interest led to incorrect descriptions with respect to the context. The systematic occurrence of this type of error would be better substantiated if it could be shown to occur in the same phase (function analysis) in another design effort. This, in fact, did occur.

In a transport cockpit design program, in which the investigator was recently participating, the design team was adapting the fighter aircraft function analysis for this effort. Two were members of the design team that participated in the fighter effort. One member was not. The same type of error occurred on the second day of adapting the function decomposition, and it occurred at the same position in the hierarchy - three levels down. The recognition of the behavior in the fighter program, and the reoccurrence in the transport program points to a systematic problem. This
systematic type of error would be amenable to the generation of memory aids to reduce the occurrence of the problem.

Subproblem 5  Do designers tend to use information sources which are closest to their place of work?

Introduction

The data examined for discussion of this subproblem were categorizations of the information sources done by the designers on the information analysis sheets. (See Appendix K.) This data was generated for the self-reported questions from the preliminary interviews.

Information Source Data

The method of information access most frequently used was face to face (151) with computer (1), the least frequently used. The average number of questions per category was 66. (See Table 25.)

Table 25. Number of Method of Information Access Items by Subject and Category.

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>SUBJECT NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1  2  3  4  5  6  7  Total  %</td>
</tr>
<tr>
<td>face to face</td>
<td>25 01 75 17 05 06 22 151 38</td>
</tr>
<tr>
<td>desk/bookshelf</td>
<td>06 00 12 29 26 36 09 118 30</td>
</tr>
<tr>
<td>phone</td>
<td>18 08 23 00 01 03 01 54 14</td>
</tr>
<tr>
<td>other</td>
<td>02 00 01 00 31 02 00 36 09</td>
</tr>
<tr>
<td>library</td>
<td>13 07 03 09 00 02 01 35 09</td>
</tr>
<tr>
<td>computer</td>
<td>00 01 00 00 00 00 00 01 00</td>
</tr>
<tr>
<td>Total</td>
<td>64 17 114 55 63 49 33 395</td>
</tr>
<tr>
<td>%</td>
<td>16 04 29 14 16 12 08</td>
</tr>
</tbody>
</table>
The correlation results for the method of information access data are presented in Table 26.

**Table 26. Correlations of Number of Method of Information Access Items by Subjects.**

<table>
<thead>
<tr>
<th></th>
<th>S2</th>
<th>N( 6)</th>
<th>SIG .156</th>
</tr>
</thead>
<tbody>
<tr>
<td>S3</td>
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<td>.2942</td>
<td>N( 6) N( 6) SIG .002 SIG .286</td>
</tr>
<tr>
<td>S4</td>
<td>.3947</td>
<td>-3127</td>
<td>.5161 N( 6) N( 6) N( 6) SIG .219 SIG .273 SIG .147</td>
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<tr>
<td>S5</td>
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<td>.2029 .2156 N( 6) N( 6) N( 6) N( 6) SIG .500 SIG .049 SIG .350 SIG .341</td>
</tr>
<tr>
<td>S1</td>
<td>S2</td>
<td>S3</td>
<td>S4</td>
</tr>
</tbody>
</table>

**Discussion**

Eight correlations were significant at .05 or better, with one additional at .10. Given the time pressure which faced the design team, the lack of computer access of information was an apparent anomaly. However, the members of the design team did not have direct access from their desktop computers to computerized databases such as the Defense Technical Information Center (DTIC), National Technical Information Service (NTIS), or SCISEARCH. The Crew Systems Ergonomics Information Analysis Center (CSERIAC) had not yet
opened. Computer database searching had to be done by going to the technical library on the base. This additional time and effort was apparently prohibitive, based on designers' perceptions of the value of information they expected to find.

Allen (1977) cited Zipf's Law (1949) in an explanation of information and communication in the workplace, saying that human beings will follow a path which they believe or perceive will result in the requirement of the expenditure of least effort over time. The information seeking behavior found in the present study is consistent with these findings.

The appearance of all three of the negative correlations for subject number two provides a parallel finding to the findings for the information type data further reinforcing the lack of contact with other people for information access.

Problem 2 - Can techniques for supporting communication among the members of the target multidisciplinary design teams be identified?

Subproblem 1 Can the technique of question concept mapping enhance communication among members of the design team?
Introduction

The data examined for discussion in this section were the two concept maps generated by two members of the design group. These are discussed with respect to the category findings from the interview analysis sheet data discussed previously, as well as for their value in supporting communication.

Discussion

The two most senior members of the design team were selected for the question concept mapping activity. Each created only one concept map. (See Appendix T.)

Figure 1 presents the overall structure of one map by showing the top level cluster labels with the relations among the clusters represented by arrows.

![Figure 1. The Overall Structure of the Font Concept Map](image-url)
Figure 2 presents the structure internal to one of the clusters by listing the questions comprising the cluster.

(Are there) any differences among the various fonts that were available to use?

(What are) recognition response times and accuracy rates on character recognition and symbol recognition?

What kinds of fonts, if any, were better than others?

Were there any differences in recognizability of fonts?

(What was the effect of) the size of the font?

Figure 2. Differences Cluster Questions

Neither designer had extreme difficulty accomplishing the task; both reported they found it too long. The team leader, in reviewing the concept maps, stated that he felt they would be useful as training tools for entry level management personnel who had 10 or so years in the domain, but doubted that they would be helpful to less experienced personnel. Both designers thought the question concept maps brought together in a relatively small (11" x 17") space, a powerful representation, and would help them illustrate what they had in mind when talking to others. Both designers also felt that the creation of the concept maps was too tedious, but that they could see the possibility of getting better at it with
practice. When asked about question concept maps as a tool for a knowledge engineering acquisition/negotiation process with their subjects (pilots), both felt that question concept maps could be useful, but didn't think their subject matter experts had the time to do them.

The same concept maps which were created by the designers were then taken to two members of the development team. These people were responsible for creating cockpits by specifying hardware and software to instantiate what the design team provides them with. They were working graphics and control code which governed the behavior of the cockpits.

Each of the developers felt that the concept maps gave them a better feel for all of the variables the human factors engineer considered with respect to choosing fonts for presentation on formats. One developer felt that concept maps, though not necessarily question concept maps, could be useful to illustrate the specification of format mechanization and interaction. Both developers agreed that something is needed to aid in communication between the design team and the development team, particularly because of the number of different disciplines involved. Both were skeptical of concept mapping as the communication tool, stating that an interface prototyping tool might better serve that purpose.

Overall, the response to the concept mapping exercise was positive, but guarded. The greatest concern was the amount of time it would take to generate maps. Whether this would be
alleviated if it could be demonstrated that maps could be reused in many design projects is unknown. It would seem that the map created for fonts, for instance, would not be very different for a fighter or a transport design problem. Automating the concept mapping process has been explored by McFarren (Eggleston, 1990), as well as automatic incorporation into Petri nets. This approach might well increase the value of concept mapping by reducing the cost to a point where it would be a valued tool. In the current state, though each of the designers and developers felt it was valuable, each felt the perceived cost too high.

Cross Check with other Methods

Examination of the high level categories identified by the design team leader in the level of question follow-up interview showed good correspondence to the categories used to identify clusters in the concept mapping exercise. The ability to cross check category labels derived from the analysis sheet data (generated from retrospective interview) with a method which is more nearly a protocol technique adds credibility to the categorization scheme, and supports the claim of the integrated nature of the knowledge acquisition methods. The convergence upon similar knowledge structures employing a range of knowledge acquisition techniques improves the confidence of the system designer that the categories are not artifacts of a particular method.
Problem 3 - Did the methods used provide an understanding of the cognition of the design problem solving process?

Subproblem 1 Can a model of the question asking process be described from the data acquired by this study?

An unanticipated finding about the question asking behavior related to the level of question asked by designers. The average level of question asked by very experienced designers was much higher than the average level of the question asked by one who was relatively new to the crew system design process. Compare the design team leader's "What are the characteristics of a high acceleration cockpit?" with a systems engineer's "What is the size of the outer box of the CRT?" It appears that it is the high level questions which aggregate the variables and relations by the nature of the way the question is asked, and by which design synthesis currently is done.

The idea of question level is not new. Schank (1987) addressed this with respect to the kinds of questions he believed would be necessary for a machine to be able to ask in order to be viewed as creative. This investigator believes that the team leader, through his understanding of the need for learning needed by the design team (which was an unexpectedly well represented category as discussed previously) through analysis, and asking the high level
orienting questions, was creating the environment for creative work by his team. This makes understanding the generation of these questions important because of the guidance they provide to the team for the synthesis of the design.

The synthesis portion of design was concerned with the aggregation of the products of the analysis. Though many analysis tools exist (Barthélemy, 1990), very few or no synthesis tools can be found. Why? This investigator believes that design synthesis is prosecuted by the generation of these high level of abstraction questions which aggregate within them, by the way the question is asked, large numbers of variables and relations germane to the design problem at hand. Then, as Abbe Laugier said "If the question is properly asked, the solution presents itself." (Cited in Coyne et al., 1990.) Not that it appeared instantly, but the high level questions asked by the experienced designer oriented and provided the context within which design team members thought about the design problem, albeit from the perspective of their own discipline.

The high level question thus places constraints on the search space to keep inexperienced designers from pursuing incorrect paths. This notion of providing the context in which design team members ask their own questions can be viewed as a way of narrowing the search space of questions to which answers will be sought, and if the generation of the high level questions can be understood, may be amenable to
providing computational support. Two questions seem to be particularly important. First, what are the triggers which cause one question to be asked and not another? Second, what are the classes of issues from which high level questions may be drawn?

Level of Question Follow-up Interview

In order to follow up on this idea, another interview was conducted with the design team leader. The analysis work which was observed was reviewed by the investigator for high level questions. The design team leader was presented with an example of a high level question relating to high acceleration cockpits, and asked how or why he generated that particular question. Some of the relevant response to the question about what triggers the high level questions follows.

First, the leader spoke about remembering questions that others had asked over time and hearing some questions repeated which indicated problems not yet solved or important recurring problems.

Second, he asked himself those questions, in the context of the current design effort, to determine which have the most impact on the current design effort.

He commented that analysis is relatively simple compared to the synthesis side - that is why the Cockpit Automation Technology (CAT) program has so many analysis tools
(Barthelemy, 1990) (because synthesis tools are so difficult to build).

The following is the dialogue in response to the trigger question with quoted material being the team leader, bracketed the investigator.

"The reason I ask all these synthesis questions is an attempt to define a solvable design problem. Hey - If we can answer this question, it will give us some good guidance to go on."

"I guess the original assumption is that answering these questions seems to be in an area that we don't have any usable tools for. But I can ask them and if somebody (on the design team) can answer them then we can begin to develop a usable approach."

"It's real frustrating to have to rely on expert judgement and opinion all the time to create a cockpit. Because the rules that we have can be adhered to and we still end up with a piece of junk."

"The problem that we have today is on the information side of things, and nobody that I'm aware of knows what the definition of good information is, or how much of it, and when. Because the (design) situation is so dynamic as you have seen, changing all the time...what was the other part of your question?"

[What caused you to ask the particular question about the characteristics of a high acceleration cockpit?] "It was to
be a high performance airplane, to be able to do things g (units of acceleration) that seemed to me to be important."

[What caused you to focus particularly on the high acceleration issue?] "I had knowledge of the scenario, knowledge of the technology, knowledge of potentially advantageous tactics for air to air engagements - which is maneuvering ability in excess of the enemy. I had also attended meetings here and there that were looking into the design and testing of a supermaneuverable airplane. Without a lot of heavy thinking, it was possible to come up with two, three or four (pilot vehicle interface) problems that would exist in a highly maneuverable airplane that probably wouldn't exist in a more conventional plane. It had been a topic of discussion there (at the meetings) that high acceleration was going to be a player. We're talking about steering this mass of talent in, generally speaking, the correct direction, trying not to perturbate large excursions from where you really want. And only somebody who has access to the data that exists outside the research team can do that steering."

High Level Question Categories

With respect to the question about classes of issues from which high level questions could be drawn, several were reported by the team leader. These include the following major categories: (1) scenario issues; (2) vehicle
characteristics; (3) vehicle environment independent of scenario; and (4) givens or constraints imposed on the design.

Scenario issues include the time frame in which the mission will be flown. This establishes the technology availability date (TAD). If the cockpit is to be flown in 1995 and the design specifies mind control over the aircraft, the design problem goes away because it is perceived as not doable within that time frame. The expected threat environment created by the enemy is a second scenario issue. This can include laser or other radiation, chemical, biological, missiles, and bullets.

Vehicle characteristics include its acceleration characteristics, its shape, its speed, endurance, and the location of humans within the aircraft. Speed determines a range of values required for display, the time density of actions required for vehicle control, and interacts to some extent with shape. Endurance affects crew facility requirements, crew augmentation requirements, and allocation of space.

The vehicle environment independent of mission includes such issues as operating altitude, and g or no g. Examples of questions stemming from these issues are: (1) Will the cockpit be pressurized?; (2) Will gamma ray protection be required?; and (3) Will methods for restraining objects in the cockpit in 0 g be required?
Constraints imposed on the design include such things as defining a baseline aircraft to be improved, specifying the use of government furnished equipment regardless of the impact on human performance, or the forced incorporation or removal of a particular aspect of technology such as voice interactive system control.

In general, the interaction of the mission scenario TAD with the other, which specifies the equipment available to do the job, and the other categories of issues, which define what the job will be and where it will be done, drive the generation of the high level design integration questions. The design derived for a particular design effort then defines the job of the pilot or crew.

Discussion of Level of Question Follow-up Interview

The comment by the subject concerning amount of information needed parallels findings with respect to the data analyzed concerning the level of resolution needed for problem topics. Level analysis was not specifically addressed by this study, but would seem to be appropriate for a follow-on.

The reported categories of major issues seem to this investigator to represent collections of categories used in this study, i.e., there were no categories used which did not fit into one of the major issues. The major categories also were found in the concept mapping exercise, further
reinforcing these categories as representing the structure of knowledge for this domain.

Summary

A model of question asking for this domain would include partitioning of high level questions into the major categories identified in the follow-up with subject one. These high level questions are understood to aggregate variables and serve the goal of focussing or steering the design team through a search space. This can be modeled as pruning the branches of a hierarchical search space in that as members of the design team have to make decisions about what questions are relevant to the particular design effort, the high level questions generated by the team leader will eliminate the need for asking some sets of questions. For example, with respect to the high acceleration cockpit question, questions about control devices must be derived. Questions about yoke type control devices would not be generated by design team members because of the lack of physical support for the arms of the pilot, and subsequent inability to perform the control task.

High level questions remain fairly stable over design efforts, that is, they are repeated. The generation of question asking support in terms of the types of questions to be asked and the relationships among high level questions to
provide structure to the design problem is one component of a support system this investigator believes important.

As high level questions are decomposed, lower level questions result. These questions begin to make contact with levels at which information support is possible. An important feature of the information response to these lower level questions is context based modification if necessary.

Subproblem 2  Does the type of question asked vary with the role on the design team?

The types of questions asked by designers of different educational disciplines were found to be different. The systems engineers asked questions which focused on such topics as RS-233 interface adequacy, power supply design, shielding to avoid cathode ray tube distortion, the requirement for heat sinks, etc. Pilots were concerned with the amount and form of information required to do the job of flying the mission, and presentation such that the pilot was not head down in the cockpit so much of the time that he could not do the out the window visual job of flying. Human factors engineers were concerned with what the systems engineer was specifying related to what the pilots were saying. An additional concern was how to mediate the transmission of information from the hardware/software to the pilots head via the design of display and control concepts which
simultaneously kept workload at an acceptable level, allowed for maintenance of situation awareness, and responded to the Military Standards which applied. One subject, a sub-system specialist was focussed on the application of one particular set of control and display technologies, but asked questions from a variety of perspectives.

In addition to differences in the questions asked by people of different educational backgrounds, different questions were asked by individual designers depending on their role on the team. One subject, working on two different design teams, with different roles on each team, asked different types of questions depending on which project was being worked. For the TACS project, systems engineering questions were asked like "How to redo the voice system to have voice activation of format switching?" while in another program, serving as test monitor, the questions were "How to develop a test plan?" or "How to test different function allocation options?".

Subproblem 3 Do different designers use different information seeking strategies?

Introduction

The data for the discussion with respect to this subproblem were follow-up interviews with members of the design team. In particular, after the analysis sheet data was
collected and analysis was begun, the investigator noticed
different numbers of information sources with respect to one
question as well as differences in the path of information
seeking.

Discussion

Various information seeking behaviors were observed.
Some subjects chose to immediately ask another person whom
they thought could direct them to an answer in the most
efficient way. Others always started with project
documentation. Some consulted professional journals first,
others only as a last resort. One finding which was
unanticipated was the need to accommodate multiple information
source responses to a single question on the analysis sheets.
It is probably almost axiomatic of the domain to say that no
single source of information is likely to contain the complete
answer for a given design question. The lack of a good
computerized database that was easily accessible, useful and
fast prevented computer access from being included in the
information search for any of the subjects.

Problem 4 - Can a set of methods to acquire knowledge to
enable identification of solutions to the following
subproblems be generated and implemented?
Subproblem 1  Did the methods identified acquire useful data on individual design problem solving?

The results from the previous discussions of interview data analyzed certainly demonstrate that the methods used for this study do provide useful data with respect to individual design problem solving with the exception of the design diaries, which provided so little data as to be of no use.

Problem solving strategies identified from the observation and confirmed in follow-up interviews that related to individual design problem solving included: island hopping, boundary finding, and crossword fill-in. Hierarchical decomposition was observed in the interview data, integration meeting transcripts, and the concept mapping data.

Island hopping is used to describe the strategy of working on one dimension of the design problem, then changing to another dimension, such as going from function analysis to doing the technology assessment. This was done for two reported reasons. The first was to alleviate not what would be termed boredom, but a feeling of being burned out with one particular aspect of work. Designers did this under their own control. The second reason was out of an individual's hands. Either some resource necessary to continue work was unavailable (meeting room, computer, access to expert) or
someone in a position of authority scheduled events or meetings that took precedence in the work schedule.

Boundary finding or constraint finding is the determination by designers of the limits within which the design on which they are working will evolve. These constraints include time and schedule, budget, hardware availability, engineering support, software development and manpower availability. These change during the course of the design, and must be sampled iteratively to maintain awareness of the boundary conditions.

The crossword fill-in is the most difficult to describe. The complexity of the domain of crew system design was such that even relatively small subregions of the domain contained an exceedingly large number of variables and interactions within the subregion as well as with other subregions. Thus, the designers were forced to create structure within these subregions by identifying known structure that hinted at what the surrounding structure should look like. The generation of a priority system to aid in a format paging scheme was an example. During an air-to-air engagement, a pilot is not going to want a landing checklist to appear as a format on one of his multifunction displays. He is going to want information about what weapons systems are currently operational, and will not want that taken away. A situation awareness display is something he will probably want, but it is not clear what priority it should have. These are three of
what may be hundreds of display formats for possible presentation. By identifying some structure - identifying probable need within a phase of flight, and some logical prioritization scheme, the designers injected enough structure to be able to proceed. This investigator saw this as analogous to getting at least one word filled in for a subregion of a crossword puzzle, in that it then provided cues or clues as to the contents of the rest of the subregion.

Subproblem 2 Did the methods identified acquire useful data on group design problem solving?

Problem solving strategies identified from the meeting transcripts that related to group design problem solving were hierarchical decomposition, peaks (depth first), plateaus (breadth first), and analogical structure importing, both from outside the current design problem and within (between subregions) the problem. Hierarchical decomposition was the most apparent strategy employed by the group. It was necessary to decompose the domain into chunks that were addressable within the limits of human capability. The function analysis done by the design team was a hierarchical decomposition based on a systems approach. The hierarchy was as much as seven levels deep, depending on which system was being addressed. Embedded within the hierarchical decomposition were both peaks and plateaus strategies.
A top level decomposition across the major functional areas was completed first. This identified the following structure underlying most of the major functional categories: (1) Determine present state; (2) Determine desired state; (3) Determine deviation; and (4) Decide action on state. (See Appendix Y for a copy of the function analysis.)

After this general structure was established (after several false starts and directions), the function analysis was pursued utilizing a peaks strategy. The design team exhaustively decomposed a major functional area before proceeding to the next. This does not imply that functional areas were not revisited. As the team learned more about the overall functional requirements for the design, areas were revisited in the light of what was learned. Thus, iteration was seen within the design process, however this does not seem to be a strategy per se.

Analogic structure import was the third problem solving strategy observed during the team meetings. The design team worked from a function analysis done previously in the same laboratory, but which was done for a bomber crew system design program. This was used as a guideline for the subregions to include in the TACS function analysis. The exact structure and wording were reworked, but some pieces were imported almost intact. Once a collected set of structure and related wording convention were established within one functional area
of the TACS design, the team freely transported it to other subregions when it applied.

Inquiry cycles were seen to occur during the design observations and interviews. Those question-asking/information seeking/solution proposing cycles iteratively refined solution sets for sub-regions of the design problem.

Subproblem 3 Did the acquisition methods used for this study differ in their efficiency, measured in terms of rate of capture of questions?

The data acquisition rate for the integration meetings was 76 questions per hour. The data acquisition rate for the interviews was 49 questions per hour. If the assumption is made that all designers with diaries (12) had them 8 hours a day for the period of observation (24 weeks for the diaries), the rate of acquisition was .003 questions per hour. While the rates were of a wide range, this was to be expected. The diary was a low priority work item. The questions recorded in the diary could be expected to be of a more general nature, and be more important to the designer, than those generated by the interview or observation methods because of the nature of the task, with its requirement of drawing questions from memory.
Subproblem 4 Did the data acquisition methods differ in required processing time to generate data in terms of numbers of questions?

Both the interview processing and the integration meeting processing required approximately two and one half hours of processing time to generate 50 questions. Within the resolution of the record keeping, there was no difference.

Some overall comments on all of the categorical raw data are in order. First, those category sets which contained other classifications and had large numbers in that category probably deserve attention in terms of providing a more complete set. Second, those sets of categories which were specific to design or the design process seemed to be more sensitive in that there were trends in the distributions. The notable exceptions were explained in terms of the findings of Allen (1977) and Zipf (1949). The categories which could be described as generic such as the information goal set, the question type set and the set relating linguistic, semantic, schematic, etc. categories showed an even or a random distribution of results. These findings were followed up by correlation analysis of the data.
Discovery of Additional Categories

During the analysis of the integration meeting transcripts, questions were identified which did not fit easily into the categorization scheme used in the analysis sheets, and which formed the conceptual basis for this dissertation. Most are administrative or social in nature, and may or may not be important for the development of a support system. The categories suggested by the integration meeting data follow.

An indication of a need for support beyond the technical categories used in this dissertation provides administrative and social categories of questions. Adding these to the survey of the question asking behavior of designers could help to make the design support system more broadly useful by extending beyond the realm of purely technical support.

The administrative categories identified were: (1) meeting related - coordination, cooperation, and control; (2) program related - coordination, cooperation, and control; and (3) interface to other organizations. The social categories identified were: (1) general polite convention; (2) inquiry about family; and (3) inquiry about extra-work plans or experiences. These categories extend the type of support possible beyond the technical issues which were the focus of this study.

For most of the technical questions, the category sets used in the present study were adequate. Some technical
categories identified were in some cases slightly different statements of categories used in the present study while in other cases they may have been at a different level of resolution and could be used to supplement the present set of categories by adding the ability to examine question asking behavior at a finer level of granularity. Technical categories identified included: (1) interpretation; (2) technical goal; (3) interdisciplinarity; (4) stopping rule; (5) validating accuracy of data/information; (6) team learning; (7) scaling/resolution of analysis; (8) representation generation; (9) path finding (Where did that come from?); (10) gaining consensus; (11) checking understanding; and (12) assumptions.

Summary

In this chapter, the data were presented, analyzed and discussed. In Chapter V, an overall discussion of the findings of this dissertation will be provided, and recommendations made for future study.
CHAPTER V

DISCUSSION AND RECOMMENDATIONS

Introduction

In this chapter, a review of the work done for this dissertation will be given, a support system model proposed and discussed with respect to the major findings, and recommendations made for future study and methodological refinement.

Review of Work

An exploratory study was conducted into the question asking and information seeking of aerospace crew system designers to develop an understanding the structure of designer behavior for the purpose of support system development. Interviews were conducted, audiotaped and transcribed; integration meetings were observed, audiotaped, and transcribed; designers kept diaries; and the investigator participated for a year and nine months as a member of a design team. Field notebooks were kept by the investigator, recording observations by the investigator which aided in the

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interpretation of the transcribed materials. Categorization analysis of interview questions was done by subjects participating in the integration meetings. These data were subjected to summary and statistical analysis. Interaction analysis was performed on the interview and integration meeting transcripts, identifying several problem solving strategies. Question concept mapping was evaluated as a communication support tool. Documents produced by the design team were collected as corollary material.

Review of Major Findings

Structure of Knowledge

Data were gathered and insight gained with respect to the categorization of questions asked and information sought during design problem solving. Categories which corresponded to particular aspects of the design process provided data on similarity of questions asked which were more highly correlated than generic categories. Knowledge structure took the form of a hierarchy for the function analysis. Various forms of importing structure were observed. (See Design Problem Solving, below.) Similarities and differences in designer behavior were identified and discussed with respect to support system development. A major finding was the existence of high level questions which guide the design synthesis process, and provide guidance for the question asking behavior of members of the design team.
Information Use

Information is needed in relatively short response cycles, and the information needs to be contextualized for the type of crew system being designed. Information access channels currently favor human sources (other persons and self-knowledge). Only one occurrence of computer based information access was reported in the present study. This suggested that if computer based information is to be provided, it must take a very different form from what is currently available to the subject population.

Design Problem Solving

Problem solving strategies identified by interaction analysis from the interview and integration meeting transcripts included: island hopping, boundary finding, and crossword fill-in, hierarchical decomposition, peaks (depth first), plateaus (breadth first), and analogical structure importing. The hierarchical decomposition of functions was particularly problematic with respect to "errors" (short term memory failures).

Bonuses

Although the premise going into the research centered on the linkage of questions and information seeking, more questions were gathered which focussed on generating structure for the design problem than those which were seeking
information. The problems upon which the design team worked were ill-defined (had low structure) and problem solving strategies dealt largely with ways of identifying organizational structure within the problem space.

The concern of the team leader with the aspect of learning on the part of the members of the design team was another unexpected finding. As members of the team generated various portions of the documentation—design scenarios, technology assessment, and function analysis—the team leader was constantly requesting updates for the team using both formal and informal briefings. Status meetings brought together personnel from both the design and development groups. The goal was shared information about the current state of development of the design, providing context for each member of the group.

Support System Model

Based on the knowledge gained from this study, the following model of a design support system is proposed. (See Figure 3.) It is this investigator's belief that what is needed for this domain is to create a computer based environment for design, rather than a tool which does design automatically (cf., Brown and Chandrasekaran, 1989). The reason for this is the extremely large number of variables involved in the design problem and the lack of formalisms regarding them.
Three main modules are included. These are: (1) a computer-based information module; (2) a communication support module; and (3) a synthesis support module. These are further explained below with support for each provided from the present research and discussed with respect to the literature. It is expected that the system would be capable of supporting a wide variety of methods and media such as those to be supported by the Education Utility (Gooler, 1986).
Computer-Based Information Module

The computer based information module has two subsections. These are an information contextualizer, and an inquiry strategist.

Contextualized Information

The lack of computer-based information seeking by the design team, the use of human sources of information for contextualized answers to questions, and the time pressure for the access of information points to the need for specialized support. Traditional databases such as DTIC or NTIS are likely to be perceived to be of low value because of the lack of contextualization. This is also true of conventional design handbooks, human engineering texts, and other currently available materials.

What seems to be needed is a computer based version of what Allen (1977) and Boff (1987) referred to as a "gatekeeper", someone who was/is a domain practitioner and tuned in to emerging technologies and aware of their probable impact on a particular domain. Although this contextualization of information is problematic in terms of how to accomplish it, the data obtained in this study certainly argue that if the system is to be of use, it is of primary importance. One possibility is the networking of the information base, at least within local organizations. With appropriate tools, information entries could be marked with
contextualizing statements, and cross referenced to Design Criteria Notebooks, to provide instances of information use in design problem solving within the context of a particular design effort. Utilization of CD-ROM technology can shrink the documentation for a given project to a size amenable to the individual designer's office.

The aerospace crew system design process requires access to more information than can be stored in the typical office space available to designers today. This along with the findings of this dissertation with respect to information seeking behaviors, in which designers tend to access sources nearest their workspace more often than those farther removed, argue for desk-top access to information sources. This is supported by Boff (1987) who indicated that in terms of information access, perceived value is not correlated with its intrinsic worth, but rather with ease of access and utilization. The categories relating to the design process utilized for this study, with some slight modifications, would form the core of the information retrieval structure. Access methods would include keyword category search, browsing, access via questions identified in this study and expanded by adding questions from other studies, and graphical interfaces generated using the concept mapping approach.
Inquiry Strategies

Support should be provided in such a way as to accommodate the various information seeking strategies displayed by designers. This includes supporting the various paths demonstrated by the findings with respect to Problem 1, Subproblem 5, where it was found that most designers went to other people first, others to their desk or bookshelf, and almost none to the computer. Again, this was probably exaggerated because there was no on-line access to information from the desktop in the workspace of the designers observed for this study. The access to other persons as information sources implies the need for electronic dialers and/or electronic mail support.

The work being done in computer supported cooperative work (Grief, 1988; Robertson, Zachary, and Black, 1990; and Galegher, Kraut, and Egido, 1990) should provide additional insight into methods for supporting information access for design.

Communication Support Module

The communication support module contains three subsections. These are question concept mapping, interface prototyping tools, and smart rooms. The communication problem between the design team and the development team in the specification and generation of crew system simulators definitely exists.
Question Concept Mapping

Question concept mapping was explored as one way to enhance communication, and was used as a knowledge acquisition technique to provide converging evidence for other methods. Response was generally favorable, however, effort expended for the amount of return was questioned due to the amount of time required for generating the maps. Automated mapping techniques such as those generated by McFarren (Eggleston, 1990) could be explored to evaluate the time burden if the process were computer based. Gordon (1990) reports using concept maps as knowledge engineering tools for hypermedia systems (McAleese, 1989) and references work done on a computer-based tool called SemNet done by Fisher (1987).

Interface Prototyping Tools

Other tools such as hypermedia rapid interface prototyping tools should be investigated as a means of providing more explicit representations of desired designs. The ability of these tools to integrate text and graphical material (McAleese, 1989) and to be engineered to fit the target population using methods such as those discussed here make it likely that some combination of concept maps and rapid prototyping tools will provide the resources for enhancing communication in that they provide concrete referents which can help transition knowledge along with procedures when system designers pass specifications to system developers.
The hypermedia tools can provide the ability to generate virtual interfaces which behave procedurally identically to the pilot vehicle interface being designed, but not having the computed inputs such as aeromodels, sensor models, and control feedback systems. These can in turn serve as part task procedure trainers for evaluation purposes, and can be maintained as a part of the record of the design process, thus providing configuration management or traceability.

Smart Rooms

Smart rooms which provide entire walls as display surfaces and serve as data capture devices would help to remove the boundaries of the standard page size for the representation of the design problem. This is seen as a combination of the Rooms extension of the Windows concept, and white boards which provide hard copy of information displayed on them. This information, once captured would then be available for further analysis, discussed later in this chapter.

The design process observed in the present study is one which is largely evolutionary in nature. It involves iterative cycles (Booth, 1989). Indeed, the cockpit design under observation was a second generation cockpit using multifunction displays. This evolutionary nature argues for the recording of design histories in the form of Design Criteria Notebooks, which, along with the knowledge transition
tools discussed above, would provide access to design decisions and implementations made in previous design efforts. Although the technology, and therefore the specific implementation of particular functionality would change, it has been the experience of this observer that a large number of the questions asked are generic. Over time, an extensive database of questions could allow a design support system such as the Designer's Associate help the designer to ask questions he may not know to ask (Boff, 1987). This is particularly critical in settings which experience a high turnover rate, with relatively inexperienced designers participating in the work.

Synthesis Support Module

The synthesis support module has five subsections. They are question asking, aggregation formulation, aggregation heuristics, aggregation evaluation, and simulation tools. The data from the interviews, design diaries, and observations seem to be incomplete with respect to the total design process in that there is no well defined synthesis phase or set of activities. The synthesis phase of the process is not documented in Kearns (1982) and the other sources about the design process (Barthelemy, 1990). This was confirmed directly with the author (Kearns, 1990). There was, however, the interesting insight discussed in Chapter IV relating to the average level of question asked by the very experienced
designer. It appears that it was these high level questions which aggregated the variables and relations by the nature of the way the question was asked, and by which design synthesis was done.

Question Asking

Given knowledge of the required functions, information, and technology available generated by the analyses of the systems approach and knowledge of the user's job, the crew system designer can begin to aggregate the components. This is the creative, synthetic part of the design process, which this dissertation claims was done in the head of an experienced designer, guided by the high level questions he asked. The high level questions act as short term memory aids by chunking the problems at a level which combines several to many variables and relations.

One type of tool which would seem to be appropriate for each of the three partitions of the design work is a question asking tool. The idea of a question-asker is not new. Eliza, Weizenbaum's (Weizenbaum, 1966) software psychiatrist asked questions and responded with another question based on the subject's answer to the previous question. Boff (1987) cites the need for a design tool which helps designers to ask questions.

Newer applications of question asking programs include Thoughtline (Miller, 1987), a speech, report and presentation
creation tool for business; and the Design for Assembly Toolkit (DAT) reported by (Vogt, 1988). These appeared in the literature after the questions asked focus had been decided upon for the present study. The DAT aided International Business Machine (IBM) in designing the IBM Proprinter for ease of assembly and reduction in number of parts. Vogt (1988) provided a sample of the questions asked when considering the design of a fastener connecting two members. The program asks three questions: (1) Does the part move?; (2) Does it have to be a different material from the two members?; and (3) Does it have to be removed for servicing? If the answer to all three is no, the question becomes "Why can't the assembly be made in one piece?" The DAT software and the design for assembly DFA approach reduced a Ford throttle body assembly by 43% in number of parts, and assembly cost by 38%. All this without replacing the engineer or reducing the requirement for the engineer's creativity. While crew system design is a substantially different domain from the application of DFA, it appears to this investigator that building question asking programs to support crew system design is achievable.

A recent experience involving the function analysis provides further credence to the notion of building a question asking tool for the support of crew system designers. This investigator is currently involved in modifying the function analysis produced by the fighter design effort which was
observed for the present study. (That function analysis was a modification of one done for a bomber program.) The present program is a special operations transport effort. Many of the elements of the function list are the same, generic, regardless of the aircraft design under consideration, and can be imported, structurally intact from previous efforts. Not only has it been possible to do that in this transport aircraft effort, but the same type of errorful behavior – getting lost as to which subheading the group was working in – occurred again, and once more it was more than three levels down in the function hierarchy. This was despite the fact that the investigator and another of the design team members had participated in the fighter study, and were aware of the previous problem.

Coyne et al. (1990) discussed the design synthesis process as optimization and evaluation, stating that "A design solution (represented by a vector of decisions) may exist explicitly in the decision space." The vector accounts for performance criteria, performance constraints, and decision variables. The questions could be constructed such that they contained phrases capturing performance criteria, performance constraints, and decision variables. It seems realistic to think that a synthesis tool, in which the representation consisted of a vector of questions, would aid the designer in arriving at design solutions that would be "satisficing" (Simon, 1973) at least, if not optimal.
Aggregation Formulation

Concept maps can be utilized to provide a tool for the formulation and representation of aggregates of design entities. The use of maps drew favorable comments from system developers in this study, and have been used as engineering tools in the development of hypermedia instructional systems (Gordon, 1990). The negative reaction to the amount of work in creating concept maps may be overcome by automating the process (Fisher, 1987) and by noting the amount of generic content common to all pilot vehicle interface design efforts. Concept map representations allow for a medium for the negotiation of structure of the system being designed (McFarren, 1987) and provide yet another tool to document the design process.

Aggregation Heuristics

Methods of clustering the products of the analysis phase of the design process are needed in addition to the question asking support discussed above. A time relation analysis of function execution is one possible technique. This would simply involve the identification of the precedent, subsequent or synchronous relation between/among functions identified in the function analysis activity.

Methods of clustering displays or controls in terms of the layout of the crew system with respect to the job of the user would provide guidance for grouping. Some of these exist
already, such as putting controls with immediate access requirements on the throttle or stick. These clustering techniques could be tested by taking hand path data with rapid prototyping tools in conjunction with a rigorous task analysis to define exactly what the context of the hand path was. The goal here would be to minimize overall hand path.

The representation of aggregation via the concept mapping technique would provide a model which would allow for a negotiated understanding of the components and relationships among components within the design.

Aggregation Evaluation

Aggregation evaluation in terms of "what would happen if" could be supported by providing Petri net representation of concept maps and allowing investigation of the effect of change vectors. The mechanization of the process has been begun by McFarren (Eggleston, 1990).

Simulation Tools

Simulation tools which allow the designer to experience the effects of human information processing limitations are being developed by Search Technology under the Designer's Associate contract (Glushko, 1990).
Summary

In summary, this study has provided insight into critical dimensions of a design support tool for this domain in this setting. Activity by other researchers interested in knowledge acquisition and knowledge engineering tools (Gordon, 1990; Zachary, 1986), in computer supported cooperative work (Grief, 1988; Robertson, Zachary, and Black, 1990; and Galegher, Kraut, and Egido, 1990), and in knowledge based systems for design (Coyne et al, 1990) indicates that the generation of a support system for crew system design based on the present research can expect to be enhanced by the findings of other researchers in related fields.

Recommendations for Future Study

Support System Prototype

It is desirable to begin the generation of a prototype design support system as described above to test component parts of the system, and assess their impact on the design process. The design support system is seen not as a design problem solver, but as providing an environment which gives the designer a number of tools in the three main support areas described above.
Additional Analysis of Present Data

Sequential interaction analysis of the integration meeting transcripts could be done to further investigate patterns of question asking and information seeking behaviors.

A comparison of the question designers thought they asked to the questions they actually asked could be generated by comparing the data from the interviews to that from the integration meetings. This would provide insight into the differences or similarities of data on questions generated by self report (interviews) as compared to observation (team meetings).

Domain Portability

It would be desirable to use this methodology for different crew system design settings such as other government facilities like NASA, Naval Air Development Center, etc. and at major airframers to determine the generalizability of the findings of this study. It would also be interesting to extend the methodology to other domains such as business planning (albeit with different categories) as a technique for identifying the structure of knowledge and information use. This would allow for tool for evaluation of its domain portability, and would further justify the development of automated methods of data collection and analysis, below.
Methodological Refinements

A number of methodological refinements suggest themselves based on the experience gained in this investigation. Methodological refinements suggested by the use of the tools and techniques employed in this study include modification of some of the tools, elimination of others, and the possible addition of new approaches. These suggested refinements, along with implementation requirements, are presented in this section.

Exploratory Interviews

The unstructured exploratory interviews were perhaps the single most important event in the entire study. These meetings with designers in leadership positions, positions which were at the level where they could authorize the investigator's observation of and participation in the design process. Establishing rapport with these designers was an important aspect of the interview. These interviews were also important in terms of conditionalizing the investigator's understanding of the design process in the context in which the study occurred. It was the first opportunity to learn about the designers' job, in the design workplace. Data from this interview was not analyzed for the study, but rather aided in the formulation of the method to be employed.
Introductory Interviews

The introductory interviews gave the subjects an idea for what the burden on the design team would be as a result of the study. These were also unstructured interviews in the sense that there was no schedule of questions prepared, although there was an agenda of topics to be discussed. The designer who was the team leader for the design group under observation was in a position to authorize the subjects to participate in the interview process as a part of their job. There was agreement between the design team leader that the participation in the interview process would be beneficial in terms of getting the team members to think about the way they went about doing their job.

The combination of the exploratory and introductory interviews provided a first exposure to the language of the subjects' design world, allowing for early understanding of designer conversations, especially those heavily laden with acronyms. Little or no change in the nature or purpose of these interviews would be required were the study to be repeated in another setting. The investigator believes that both would still be required. Data from this interview were not analyzed for the study, but rather aided in the modification of the proposed methods.
Preliminary Interviews

The preliminary interview methods were the subject of two stages of generate and test. The reason for this was that they were the first of the method set which would contribute data to be included in the study and analyzed. The practice allowed the investigator to get the timing and interaction of the interview refined. Feedback from the initial pilot subjects resulted in modifications mostly in terms of reducing some of the original question set, and comments on the appropriateness for the support system their company was developing. The second set of pilot subjects demonstrated the interview techniques and schedule to be effective in terms of acquiring questions asked in the context of the problem solving in real world contexts. One possible modification might be to have subjects go back to any project documentation following the interview to see if that would jog their memory as to additional question topics. The method of beginning the interview with relatively open questions and becoming progressively more closed seemed to work well. It allowed the subjects to think at a broader, memory jogging level first, then add detail as the interview progressed. The investigator did not request subjects to provide copies of documentation mentioned during the interview. This was deferred to the follow-up interview to avoid appearing pushy.
Follow-up Interviews

The structure of the follow-up interviews was generated following transcription and analysis of the preliminary interview. Each schedule of questions was tailored to the individual designer, and followed up on topics or issues raised in the preliminary interviews. This was the third interaction with each subject at a minimum, therefore, requests for documents relevant to the designers work was done in this interview.

Analysis Sheet Techniques

The analysis sheets provided only for single information sources to be recorded in response to one question. They needed to support the recording of multiple information sources with respect to one question, including the generation of an information search path. This would make clearer the different search strategies used by different individuals.

The analysis sheets were modified by the feedback gained in the two practice sets of interviews, but were not themselves subjected to piloting in the sense of asking subjects to use them to analyze interview questions. Future studies should incorporate piloting such tools prior to data collection.

It would be helpful to develop methods for automating the analysis sheets by searching the transcripts for questions, and copying the question directly into the analysis sheet.
file. In this study, the questions were printed out one to a page in the appropriate position on the first page of the analysis sheet, then used as the sheet on which to print the first page. If the means were available to have subjects directly record their analysis into electronic form, this would speed the data compilation tremendously.

Diary Approach

The diaries were not a useful tool in the sense of providing large amounts of data. Subjects provided feedback indicating that it was too much of a burden to get the diary out and record questions even as infrequently as twice a day. Some indicated they forgot about the diary. It would seem that this method is intrusive and burdensome enough on the individual that some form of additional compensation would be required in order to get this tool to work at a level which would provide reasonable amounts of data. Perhaps providing each subject with audio tape recorders rather than writing in a notebook would work, but it seems unlikely, given the experience of this study. The only way to get designers to provide the information such as the diaries requested may be to make that a compensated part of their job. Even then, this investigator doubts the method would work, partly because of personal experience in trying to keep a similar record during subsequent work on crew system design.
Observation Techniques

The investigator was acting in the mode of a naturalist while doing the observation of design problem solving. A field notebook was used to record observations about design team meetings, apparent insights into the design process based on observation, and observations or insights with respect to other designer behaviors (individually or in small subgroups). Time and date were attached to each observation. Team members participating in integration meetings were recorded, and notes about each meeting were written as the meeting occurred. It would be helpful to create a daily debriefing outline to stimulate response to particular observation or acquisition issues.

Interaction Analysis Techniques

The examination of the meeting transcripts was the most time consuming phase of the study. An estimated two hours was required for one pass through a transcript. Automation of question extraction would be an aid to efficiency as would the automation of question/card printout.

The supervision of transcription personnel was an area in which the investigator had no prior experience. One item which was foreseen was the need for the creation of a transcription support document before beginning the project. This was added to as the work continued. However, incremental delivery of the product (transcripts) should have been
scheduled. The long wait for a backlog of work hindered analysis and delayed finishing the project.

The generation of forms from sources on categorical aspects of design, and their translation into subject-ready data acquisition tools through to report ready copy could be aided by having a form tool available in addition to a word processing package. Reformatting of forms when categories were pruned or expanded took inordinately large amounts of time.

The subject authorization sheets and personal profile sheets could be directly adapted for a future study. The analysis sheets would need to be modified as to categories, and a mechanism must be provided for multiple information sources with respect to a single question.

Automated Support for Data Collection and Analysis

The automatic transcription of integration meetings and interviews via voice recognition systems would greatly reduce the amount of processing time required for similar studies, and allow for the generation of large amounts of data for analysis and comparison. The technological feasibility of this is a point of concern. An automatic question extraction tool would then be valuable to flag questions for later analysis.

The sequential interaction analyses mentioned above could be compared with pattern recognition via neural nets to
evaluate a means of automating the pattern identification process.

The complete automation of the methodology in the design process as described above could provide a meta-monitoring capability from which a greater understanding of the design process might emerge.

Summary

The contributions of this dissertation addressed some of the general concerns of the human-computer interaction community by providing a structured approach to capturing knowledge about users for the support system design process. It addressed some of the concerns of the crew system design community by applying the methods to the domain of crew system design, laying a foundation for continuing research in this area. Insight was gained into deficiencies in the design process itself, and suggestions made as to how to proceed to correct those deficiencies.

In summary, the lack of appropriate tools supporting crew system design synthesis or computer based information seeking, the occurrence of high level questions in those individuals who are responsible for leading design efforts, and the types of repeated errors seen in the same phase of different design efforts point to the need for a crew system design support tool which helps the designer ask the right question at the right time in the design process, and deliver contextualized
information relating to that question. Technology will change, the design efforts will have slightly different foci, but the questions which collect and focus the attention of the design team are expected to remain stable and therefore supportable by computer based tools.
APPENDIX A

SUBJECT AUTHORIZATION DOCUMENT

This is the document subjects were asked to sign prior to participating in the study.
SUBJECT AUTHORIZATION DOCUMENT

You have been selected as subjects for a study of question asking and information seeking behavior in crew system design. This data is being collected in an effort to better understand designer behavior in the crew system design process. Any questions you may have about this work may be addressed to:

James McCracken at Maculay Brown, Inc. in Dayton, OH
513-426-3421
Daniel Sewell at Search Technology, Inc. in Atlanta, GA
404-441-1457

You will be requested to fill out questionnaires characterizing your crew system design behavior in a variety of ways. It should be clear that there is no right or wrong way - we are interested in your way of asking questions and seeking information. You will be asked to keep a diary of your daily question asking and information seeking behaviors, and to further record those behaviors on analysis sheets which will be provided. Interviews will be conducted with you based on the information from the analysis sheets. Interviews will be tape recorded; the tapes will be transcribed and subjected to protocol analysis.

We will maintain this data as unclassified, therefore, if we discuss a classified area, the tape recorder will be turned off. Classified discussions must be kept at a secret or lower level due to the researcher's clearance. We recognize that complete avoidance of classified information may be impossible; if so, we would appreciate your help in maintaining this project as unclassified by whatever means you deem necessary.

The following points outline your rights as a participant in the study.

1. The researcher will maintain the subject's confidentiality and anonymity, unless that right is specifically waived.
2. The researcher will prevent raw or processed data from being linked to a specific subject by coding all items of data with a separately maintained key.
3. Access to even coded data will be limited to a need to know basis.
4. Subjects will have the opportunity to review the data if they so request.
5. Subjects may withdraw from the study at any time, without justifying the action.
6. Subjects' participation is entirely voluntary.
7. Given the nature of the data, subjects will allow the researcher to use quotes from the data to illustrate points in publications, presentations, etc., with the stipulation that the subjects' anonymity be maintained.
8. This document has been prepared covering the steps enumerated above, and a sign-off space for subjects' signature and the date is provided in which the subject will acknowledge having read and having agreed to the points outlined above as a condition of signing.

Subject ________________________ Date __________
APPENDIX B

SUBJECT PROFILE FORM

Each subject provided personal information on the following form. This was used by the investigator to gain an understanding of the background of individuals in the subject pool and for generating the number of information items for the plotting against creativity ranking.
SUBJECT PROFILE FORM

PROFILE - BACKGROUND INFORMATION

1. Name ________________________________

2. Age _______

3. Organization ________________________________

4. Educational background

   _____ BS
   _____ MS
   _____ PHD
   _____ other (describe) __________

5. Since you received your most recent degree, have you taken any additional scientific, engineering, math or computer science classes?

   _____ a. yes/no
   _____ b. how many?
   _____ c. number of years since last course?

6. Number of years of technical experience in crew system design.

7. Work experience including military. (job titles - time spent)

   List all major design efforts. (program name - time spent)
8. Please check all of the following crew system design elements with which you are directly involved in your work.

___ Crew complement
___ Seating Requirement
___ Life support systems
___ External visual requirements
___ Safety/Accident prevention
___ Ejection/survival
___ Vehicle handling qualities
___ Personal gear
___ Training requirements
___ Battle damage considerations
___ Training systems/equipment
___ Displays
___ Controls
___ Ingress/egress
___ Safety/Accident prevention
___ Subsystem integration
___ Crew station layout
___ Crew comfort
___ Reliability
___ Human-system operability
___ Maintainability
___ Others

9. Please check all of the following design-related task that your job requires you to perform.

___ Define operational requirements
___ Develop system performance criteria
___ Analyze operational requirements
___ Develop system functional specifications
___ Function analysis
___ Man-machine function allocation
___ Crew system interface analysis
___ Task analysis
___ Error analysis
___ Part-system mockup and simulation
___ Crew system layout
___ Crew system operating procedures design
___ Instructional system development
___ Engineering simulation
___ Detailed design
___ Prototype development
___ Field testing
___ System production
___ Sustaining engineering
___ Other
10. We are interested in your sources of information. From your last completed project, identify the technical obstacles or subproblems you had to resolve in the course of that job. Please indicate the sources of information especially useful in overcoming this obstacle.

___ attending papers at conventions
___ attending symposia at conventions
___ scanning or reading of journals
___ informal discussion at conventions
___ preprints, reprints, or abstracts from author
___ books or monographs
___ informal discussion with colleagues in your group
___ informal discussion with colleagues outside your group
___ verbal or written reports from assistants
___ your own empirical study
___ your own experience
___ your own intuition
___ other- please explain

11. Please list as many written information sources that you can think of that you have used or referred to regularly in the past (e.g., AFSC Design Handbook, IEEE Standards, a particular scientific paper, a particular textbook, computer manuals, etc.).
12. Please indicate which of the following periodicals you subscribe to, and which you read regularly.

<table>
<thead>
<tr>
<th>Periodical</th>
<th>Subscribe</th>
<th>Read Regularly</th>
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<td>Others - Please specify.</td>
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SUBJECT PROFILE SUMMARY

This document provides a summary of the age, experience and educational profile of the subjects included in the study. This was taken from the completed subject profile documents.

Age range - 25 to 67 years

Average age - 39 years

Experience range - 3 months to 40 years

Average experience - 12.7 years

Degree levels - B.S. - 9 - B.S., 2 - M.S., 1 - Ph.D.

Degree areas (highest degree only) - Experimental psychology - 2, Industrial & systems engineering - 2, Industrial engineering - 1, Cognitive & experimental psychology - 1, Business Administration - 1, Human factors engineering - 2, Human factors psychology - 1, Electrical engineering - 1, Biology - 1.
APPENDIX D

CONTEXT DOCUMENT
Both the Flight Dynamics Laboratory and the Armstrong Aerospace Medical Laboratory are part of the Air Force Wright Aeronautical Laboratories, located at Wright Patterson Air Force Base, Ohio.

The Air Force Wright Aeronautical Laboratories (AFWAL) are also a part of ASD, and are located at Wright-Patterson Air Force Base, Ohio. AFWAL includes four major organizations: the Flight Dynamics, Materials, Avionics, and Aero Propulsion Laboratories - and is organizationally located under ASD. AFWAL was established to combine common laboratory overhead, management, and support functions.

The Flight Dynamics Lab is located in building 146 at Wright-Patterson AFB, Dayton, Ohio. Current aircraft programs include the B1-B, T-46A Next-Generation Pilot Trainer, HH-60A Nighthawk combat rescue helicopter, C-17 airlift aircraft, enhancements to the KC-135 tanker, continued production and improvements to the TR-1 tactical reconnaissance aircraft and the F-15 Eagle and F-16 Fighting Falcon fighters, procurement of C-23A European distribution aircraft, production of C-12F and C-21A aircraft to replace CT-39's, lease/buy of C-20A special mission aircraft to replace the aging C-140's, the study and design of a transatmospheric vehicle concept, improvements to the B-52 force defensive systems, and the alternate fighter engine for F-15 and F-16 aircraft. The Flight Dynamics Laboratory (FDL) is concerned with the development of flight-vehicle technology. Specific technical areas include structural design and durability, vehicle dynamics, vehicle equipment, environmental control, crew escape and recovery, survivability and vulnerability, flight control, crew station design, flight simulation, performance analysis, aerodynamics, configuration synthesis, and technology integration. Test-beds for flight-control technologies include AFTI/F-16 and DIGITAC and the X-29A forward-sweptwing (jointly with DARPA) and AFTI/F-111 mission-adaptive wing. The later two are technology demonstrators for new wing designs. Additionally, design studies are under way for a short takeoff and landing and maneuver technology demonstrator.
The purpose of the work done by one design engineer who leads the design group of interest in this study is to plan and direct advanced development research to further the knowledge involved in crew system interface technologies, to create analytical design and evaluation procedures to be used in development applications by design engineers, and to serve as an expert consultant and technical focal point for the research and development work accomplished by others. This work effort has a significant impact upon the direction of work of other researchers within the Government, industry, and universities in the man/machine interface area. This impact is both national and international. The group provides support to the Integrated Control and Avionics for Air Superiority (ICAAS) advanced development program in the area of pilot-vehicle interface and system integration. Guidance is provided to other Laboratories and System Program Offices regarding their objectives and plans for specifying ICAAS interface design requirements.

The group undertakes activities to advance the theoretical knowledge base and to develop unique approaches to allow pilots of fighter aircraft to successfully handle simultaneous events which occur in multiple target air combat engagements. They support related advanced development programs within AFWAL, other Air Force and DoD organizations, and provide technical consultation to NASA and the FAA. They demonstrate advanced control/display technologies and cockpit designs using laboratory mock-ups, simulation facilities, and flight test aircraft, relating experimental results to projected operational requirements based on crew workload, pilot acceptance, mission responsiveness, and projected system performance.
APPENDIX E

EXPLORATORY INTERVIEW AGENDA

This outlines the questions used as a point of departure for the exploratory interviews conducted with three subjects with an average of 29 years of experience.
EXPLORATORY INTERVIEW AGENDA

1. The purpose of this interview is for me to gain insight into the nature of the design work as you and your coworkers pursue it. I am interested in finding out specific projects you have participated in or led, current projects in progress, and projects which are planned for execution in the near future. Can you begin by describing the type of design work you do?

2. I would like to acquire contextually relevant documents (to the design process as practiced on-site). Do you have documents which I could have or get copies made of, which describe the design process or document it in a way such that I can increase my understanding of what it is you do?

3. Are you in a position to allow the me to observe the designers/design team? Would you be willing to do so?
APPENDIX F

INTRODUCTORY INTERVIEW AGENDA

These questions were directed to the group leader in order to get feedback to the preliminary set of data collection methods for this dissertation.
INTRODUCTORY INTERVIEW AGENDA

1. I would like to get a preliminary reaction to the basic concepts of the proposed data acquisition approach. There are four major data acquisition techniques I would like to employ: (1) interviews (taped); (2) analysis of data from the interview transcripts; (3) meeting observations, including taping the meetings; and (4) participation as a member of the design team - sort of the George Plimpton of crew system design.

2. Here are some sample descriptions of what I propose to do. I would like to get your feedback in terms of ways of modifying the prototype acquisition materials.

3. Given this set of materials and proposed techniques, do you feel comfortable with my proceeding to develop these and execute the data collection?
APPENDIX G

OUTLINE OF GROUP PRESENTATION

This is the outline of the presentation made to the design team prior to data collection.
OUTLINE OF GROUP PRESENTATION

1.0 INTRODUCTION

1.1 Designer's Associate
1.2 Dissertation
1.3 Design

2.0 PURPOSE

The purpose of the data collection is the characterization of the statements designers make when seeking information in the course of design problem solving.

3.0 METHODS

3.1 Personal data forms
3.2 Interviews
3.3 Observations

4.0 PROCEDURES

4.1 Plimpton
4.2 Preliminary interview
4.3 Diary/analysis sheets
4.4 Follow-up interviews
4.5 Integration meeting attendance
4.6 Corollary observations

5.0 MATERIALS

5.1 Audiotape
5.2 Profile document
5.3 Diary
5.4 Analysis sheets

6.0 EXPECTED BENEFITS

6.1 Understanding of patterns of information seeking in design problem solving.
6.2 Increased awareness of information sources for crew system design.
6.3 Understanding of the criticality of information to design problem solving.
6.4 Understanding of cognitive processes in design.
6.5 Increased awareness of components of the problem solving process.
APPENDIX H

SCRIPT OF GROUP PRESENTATION

This is the script of the presentation outlined in Appendix G. It was not read verbatim, but was rehearsed and available for reference during the presentation.
SCRIPT OF GROUP PRESENTATION

INTRODUCTION  The Designer's Associate is a program originating out of AAMRL here at Wright-Patterson. Its purpose is to enhance the access and utilization by designers of information from a range of technical areas, as well as information generated within the design process. The Designer's Associate will be based on a psychological understanding of designer's, a systems engineering perspective of the design process, and state-of-the-art machine intelligence concepts. My dissertation is centered around the characterization, modeling, and evaluation of a model of the access and use of information in design problem solving. The data collected here is the material for my dissertation. We have no a priori design

PURPOSE  The purpose of the data collection is the characterization of the statements designers make when seeking information in the course of design problem solving in different contexts.

METHODS  The personal data forms request a number of items to help me understand your personal background, and provide context for the interpretation of the data. It is to be expected that each of you will have different patterns of question asking and information seeking in doing your design work. The data from the personal profile will allow me to determine whether any of the differences are systematic, and/or interesting. The initial interview will request your views about design and self-report information about design information seeking. We will go through a design problem as a talk aloud protocol to practice for later interviews, and to get your particular approach to design problem solving. They will be audiotaped. The interviews which we do weekly will be follow-ups to the information recorded in the diary and the analysis sheets. These will be talk aloud protocols and will also be audiotaped. I will be doing observations of your design team integration meetings as well as spending some time just observing while you do your work. I will not be an active member of the integration meeting. I will be taking notes to see if patterns of group interaction are evident. Design problem scenarios will be generated in which you will be asked to respond to a specific design problem. These will be talk aloud protocols, and will be audiotaped.

PROCEDURES  I will be playing the George Plimpton of crew system design for the first two weeks. I will not even begin the preliminary interviews until I have a better idea of what it is you really do. During that time, I will be recording
the same data I will be asking you to record, in order to refine my method. The preliminary interviews will occur during the first week of the data collection period, and will take about an hour per person. The diary/analysis sheet procedure will begin during the first week of the data collection. Any questions arising about the diary or the analysis sheets should be raised at that time. Please feel free to stop me at any time. The diaries will be picked up two days before the interview. I will xerox them and return them to you the following day. I will pick up the analysis sheets two days prior to our scheduled interview day, in order to prepare my agenda for the interview. The first follow-up interview will occur in the week following the preliminary interview, and will cover the stated goals, and your first week of diary and analysis sheet material. This will allow us to refine our technique for the most efficient data acquisition. During all of the interviews we do, it will be important to refrain from discussing classified information. My clearance will be on file here, so that I will not interfere with your normal work when I am around, but for reasons of efficiency, we do not want to deal with classified information. I will attend integration meetings, taping them and recording group interaction dynamics. Corollary observations will be made which will consist of my own field notes. These are to help me interpret my data, and increase my understanding of the context in which you work. The design scenarios will be design problems created specifically to elicit design problem solving information seeking behaviors from you. They will occur later in the data collection period, after being piloted on subjects elsewhere.

MATERIALS The audiocassette recorder I will be using is a Harris Lanier microcassette recorder. The profile document (PASS OUT) requests a good deal of information regarding your experience in crew system design. The diary is a small (SHOW) spiral notebook which will be used to record your design questions and information sources as they occur during the normal working day. The instruction reference for the diary is found in the same notebook as the analysis sheets. (GO OVER THE INSTRUCTIONS) The analysis sheets are a series of checklists covering various aspects of crew system design problem solving and information seeking. They will be kept in a looseleaf notebook on your desk, and will contain instruction sheets for the analysis sheets, the diary, and a glossary of terms used in the analysis sheets.

EXPECTED BENEFITS It is hoped that we will all gain a better understanding of patterns of information seeking in design problem solving. You will, as a matter of course, become more aware of the channels of information you tap in the course of doing your job. It is possible that you will become more efficient in your information seeking as a result. As a
result of my recording of the information sources each person
uses, and the sharing of these sources, there may be an
increased awareness of the available information sources for
crew system design. Because of the emphasis on the various
stages and types of problem solving, you may expect to gain an
increased understanding of the criticality of different types
of information to various stages of design problem solving.
As the data collection progresses it is hoped that a clearer
understanding of some of the cognitive processes underlying
crew system design will become apparent in terms of patterns
in the data.
APPENDIX I

PRELIMINARY INTERVIEW QUESTIONS

This is the interview schedule conducted with 18 subjects. The results were used to identify subjects who would participate in the follow-up interviews and who would be observed in the design process. The questions generated by this interview provided the data for the analysis sheets completed by designers.
PRELIMINARY INTERVIEW QUESTIONS

1. I would like you to recall as many specific problems in crew station design as you are familiar with? I will be taking notes to remind us later of the different problems. There are many kinds of problems in crew station design. These can be technical crew system design problems, organizational, policy problems or regulatory problems. Give me a series of as many problems as you can think of.

2. We will go through each problem and answer a series of questions. It is important to cycle through the following questions for each problem. (READ THE PROBLEM TO THE SUBJECT) Does the problem vignette fall into one of the following categories?

a. system configuration
b. display parameters
c. controls
d. formats and coding
e. pilot-system dialogue
f. function allocation
g. crew protection and life support
h. operator performance issues
i. training device design
j. design methods

What was the problem? Can you more clearly define it?
RECALL THE PROCESS YOU WENT THROUGH TO IDENTIFY THE PROBLEM. IT MAY NOT HAVE BEEN A FORMAL PROCESS, BUT PLEASE DESCRIBE IT TO THE EXTENT POSSIBLE. Did it arise at the stage of problem definition or in conceptual design?

How did the problem unfold?

What kind of "ripple effects" were created?
RECALL THE PROCESS YOU WENT THROUGH TO SOLVE THE PROBLEM. IT MAY OVERLAP WITH IDENTIFICATION AND IT MAY NOT HAVE BEEN A FORMAL PROCESS, BUT PLEASE DESCRIBE IT TO THE EXTENT POSSIBLE. How did you address the problem? Can you recall instances where you had a question? Can you phrase how you would ask that question? Can you recall instances where you sought information? Can you describe how you sought that information? Were you able to find the information you needed? Can you recall instances where you sought information or had a question, got some information, and later discovered that there was better information available to you at the time you originally worked the problem? Can you recall instances where you found information you thought was what you needed, but later realized it was either deficient or wrong?
Having gone through this process for each of the design problems described, would you think about the design process in general. After all, this is what you do that is special and that special process is what we are interested in understanding.

What do you consider to be the components of the design process and how the design process works? Take one of the design problems you have just described and describe the design process within the context of that design problem. Do not describe how you solved that problem but, instead, think about and describe the process of designing and how it works.

GOALS

Can you identify goals within the design process? (particularly multi-level goals)

ASSUMPTIONS

What assumptions can you identify that went into the design inquiry process? Are there classes of constraints, operators or relationships which bound the design task in ways similar to assumptions?

INFORMATION

How much time do you now spend accessing information? Is there time window you can specify? Is there a particular organization of information (WRT function, structure, behavior e.g.) that would aid in the design process? How heavily weighted are the cognitive dimensions as compared to anthropometric or perceptual dimensions?
ERRORS

Are there particular classes of design inquiry errors you can identify, particularly WRT stage of design? Do you have any insight into solutions for particular classes of error?

DECISION MAKING

What are some key decisions in the design process? How large a part does/did baselining play? Are there particular "tricks" you use in the design process? analogy, symmetry, degrees of freedom -

INTERPERSONAL

What interpersonal factors - cooperation/competition etc. do you feel contributed to or hindered the design inquiry process?

TRAINING/IMPACT

Do you consider questions about training for a system you are helping to design in doing your crew system design work?
Having gone through this process for one of your own design problems described, would you think again about the design process in general.

Please think about what you consider to be the components of the design process and how the design process works. Take the following problem and describe the design process within the context of that design problem. Do not describe how you would solve that problem but, instead, think about and describe the process of designing and how it works.
APPENDIX J

DESIGN DIARY INSTRUCTIONS

These are the instructions to the designers as to the procedure for completing entries in the design diary.
DESIGN INQUIRY DIARY INSTRUCTIONS

You are being asked to keep a diary of your daily inquiry behavior. First, brevity must be stressed. We do not want you to feel burdened by the diary. It is simply a tool to jog your memory when you complete the analysis sheets. However, if you feel there are interesting insights you can provide, please feel free to use the diary to record those. Please keep the diary with you during your daily schedule. We would like you to record any questions you may be trying to answer—whether they lead to information seeking behavior or not, as long as they pertain to your job. These may be technical, organizational, or other questions. We would like you to record who you talked to or where you went to seek information to answer the question, and some note about how long you spent in that information seeking activity.

If you believed information was available about your question, but were unable to find it where you thought you would, please record your conjecture about where you thought you could find the information. Please keep in mind that information sought implies a question, and record those information seeking events in the form of questions. Finally, please record the source from which you finally received the answer to your question. Please remember that these will be used to fill out your analysis sheets: become familiar with the analysis sheets, and take enough notes in the diary to fill out the sheets. Record one behavior to a page—if you run out of room, we will supply a new notebook. Please date each entry.
APPENDIX K

ANALYSIS SHEETS

These are blank analysis sheets identical to the ones used by subjects to analyze preliminary interview questions.
QUESTIONS ASKED ANALYSIS SHEET

Please write your questions as clearly as possible, then check applicable items below. You may check more than one item on all questions.

1.0 What dimension of the design most closely fits the question you asked?

[ ] Functionality
[ ] Performance
[ ] Design process
[ ] Interaction effects
[ ] Physical characteristics
[ ] Maintainability
[ ] Trainability
[ ] Organization
[ ] Integration
[ ] Aesthetics
[ ] Resources
[ ] Reliability
[ ] Safety

2.0 What phase of the design problem caused you to ask this question?

[ ] Problem formulation
[ ] Information retrieval
[ ] Answer formulation
[ ] Synthesis
[ ] Analysis
[ ] Constraint finding
[ ] Learning
[ ] Evaluation & judgement

3.0 What was your information goal when you asked the question?

[ ] Verification - of known information
[ ] Clarification - of known information
[ ] Acquisition - of new information
[ ] Other (describe on back)

4.0 Can you categorize your question type?

[ ] Why - does, is, was, would, could, etc
[ ] How - does, is, was, would, could, etc
[ ] Yes/no
[ ] Finding causal link - what caused some effect?
[ ] Finding component - what needs to be added?
[ ] Other (describe on back)

5.0 Would you describe the question as:

[ ] Linguistic - knowledge of language of the problem
[ ] Semantic - knowledge of facts about the world
[ ] Schematic - knowledge of problem types
[ ] Procedural - knowledge of performing a sequence of operations
[ ] Explanative - knowledge adding to your understanding
[ ] Strategic - knowledge of how to use techniques in solving a problem, such as setting subgoals
[ ] Other (describe on back)
INFORMATION ANALYSIS SHEET

Please write a brief description of the information you acquired and answer the following questions about that information.

1.0 SOURCE - Please check all that apply.

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<th>Type</th>
<th>Access</th>
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<td>journal/periodical</td>
<td>bookshelf or desk</td>
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<tr>
<td>technical report</td>
<td>computer</td>
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<tr>
<td>design handbook</td>
<td>phone</td>
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<td>project documentation</td>
<td>face to face</td>
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<tr>
<td>statement of need</td>
<td>other</td>
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<tr>
<td>another person</td>
<td></td>
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<tr>
<td>own knowledge</td>
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<td>other</td>
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2.0 QUANTITATIVE DIMENSIONS - Please write the approximate number of each of the following, otherwise check the appropriate categories.

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<th>Length of conversation</th>
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<td>10-30 minutes</td>
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<tr>
<td>100 or more pages</td>
<td>30 or more minutes</td>
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</table>

Time to access this information. Time to evaluate this item of information or document.

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<th>Time to access this information</th>
<th>Time to evaluate this item of information</th>
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<td>more than 5 days</td>
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3.0 QUALITATIVE DIMENSIONS - Please mark your estimate of each qualitative dimension for the information you acquired.

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<td>Usable in solution</td>
<td>Not usable</td>
</tr>
<tr>
<td>Low complexity</td>
<td>High complexity</td>
</tr>
<tr>
<td>Low precision</td>
<td>High precision</td>
</tr>
<tr>
<td>Low specificity</td>
<td>High specificity</td>
</tr>
<tr>
<td>Low credibility</td>
<td>High credibility</td>
</tr>
<tr>
<td>Needed for solution</td>
<td>Not needed</td>
</tr>
</tbody>
</table>
1.0 TASK - Please check the following design tasks that best describe what you were doing when your question or need for information arose.

- Analyze operational requirements
- Define operational requirements
- Develop system performance criteria
- Develop system functional specifications
- Function analysis
- Man-machine function allocation
- Crew system interface analysis
- Task analysis
- Error analysis
- Part-system mockup and simulation
- Crew system layout
- Crew system operating procedures design
- Instructional system development
- Engineering simulation
- Detailed design
- Prototype development
- Field testing
- System production
- Sustaining engineering
- Other

2.0 TOPIC - Please check topic(s) applying to the problem you were working on.

- Crew System Configuration
- Displays and Controls
- Cost-effectiveness of Design
- Life Support Systems
- Operator Performance
- Other
APPENDIX L

FOLLOW-UP INTERVIEW AGENDA
FOLLOW-UP INTERVIEW AGENDA

1. You asked question X while working on Y and had hypothesis/goal/plan Z with respect to obtaining some information.
   1.1 Is this an accurate description of the problem?
   1.2 If not, how would you modify what I described?
   1.3 Why would you make those changes?

2. Was there a reason for the pattern or sequence I have described? (easiest, best possible answer, serendipity)

3. Were there constraints which led to this pattern? (time, cost, knowledge)

THE FOLLOWING QUESTIONS RECOGNIZE THAT YOU MAY HAVE LEARNED SOMETHING ABOUT THE INQUIRY PROCESS (QUESTIONS/INFORMATION) SINCE YOU WORKED ON THE PROBLEM. PLEASE GIVE US ANY INSIGHT YOU MAY HAVE GAINED.

4. If you were working the same problem now, would you ask the same question?

5. If not, how would you rephrase it?

6. Why would you rephrase it that way?

7. Were there cues in the original problem that caused you to ask that question?

8. If you were working the same problem again, would you have gone to a different information source?

9. If so, why?

10. You categorized your question as (factual, procedural, explanatory). Was this accurate?

11. Would you change the certainty you placed on the conjecture about finding the information you sought?

12. If so, why?

13. Discuss the reasons for the ratings given for relevance, understandability, usableness, and level of complexity.

14. Discuss the quantitative dimensions from the perspective of the cost of information access and use.
15. Discuss the source selected from the perspective of the cost of information access and use.

16. Discuss the reasons why information was sought.

17. You classified the problem you were working on as [A]. What characteristics of the problem made you choose that category?

18. Was the information in a format in which it was easy to incorporate into the problem solution?

19. If not, what format would you prefer. ASCI data files for simulation or rapid prototyping for example.

20. Was the access mode satisfactory?

21. If not, why not?

22. What would you prefer as the access mode to that type of information?

23. What would have helped you get the information faster?

24. What information did you not find?

25. What information seeking procedures were ineffective?
ANALYSIS SHEET GLOSSARY

This glossary defines terms found in the analysis sheets which might be interpreted differently by subjects. The numbers in this glossary correspond to the numbers found on each of the analysis sheets.

Questions asked analysis sheet

1.0 Qualitative dimensions

1.1 functionality - fulfilling the stipulated needs
1.2 performance - efficiency or effectiveness of the components; a measure of the ability of a system to perform its functions
1.3 design process - considerations of the generation of the design
1.4 interaction effects - problems dealing with the effects of competing aspects of the design process
1.5 physical characteristics - the size, color, material makeup, or arrangement of the components of the crew system
1.6 maintainability - factors influencing the inspection and overhaul of the various components of the crew system; the ease with which maintenance of a functional unit can be performed in accordance with prescribed requirements
1.7 trainability - factors influencing the difficulty or cost of learning to use the system
1.8 organization - the effects of the organization within which the design work is being done on the design question
1.9 integration - factors included in the resolution of tradeoff decisions in the design process; the process of combining software elements, hardware elements, or both into an overall crew system or subsystem
1.10 aesthetics - consideration of factors which enhance or impinge on the overall impression of the crew system
1.11 resources - consideration of issues of cost, time, project deadlines, knowledge, technology which provide constraints to the design process
1.12 reliability - the probability that a device will perform its intended function for a specified period of time under specified operating conditions
1.13 safety - factors affecting the well-being of the operator, and the crew system.

2.0 Aspect of design problem

2.1 problem formulation
2.2 information retrieval
2.3 answer formulation
2.4 explanation
2.5 learning
2.6 information control
2.7 synthesis
2.8 analysis
2.9 constraint finding
2.10 evaluation & judgement

3.0 Information goals
3.1 verification - seeking information leading to confirmation of something already known, usually to increase confidence in the accuracy or truth of something already known
3.2 clarification - seeking information leading to reduction of confusion about an issue
3.3 acquisition of new information - seeking knowledge previously not known; gaining new perspectives on a problem situation

4.0 Question type
4.1 why - questions which ask about the purpose of an action or design choice
4.2 how - questions which ask about the way some goal of the design process is to be accomplished
4.3 yes/no - questions seeking to confirm/disconfirm a specific piece of information
4.4 what - questions which ask what a specific component is
4.5 occurrence - causal chain - questions which inquire about the interrelationship of a series or actions or states
4.6 component - missing part - questions which inquire about the effects of deleting a component

5.0 Kind of knowledge
5.1 linguistic - knowledge of the English language, such as recognizing words
5.2 semantic - knowledge of facts about the world; a question about a specific object or the value or some variable, either of which is perceived as having some objective reality
5.3 schematic - knowledge of problem types, such as the idea that checklists resetting is a diagnosis (debug) problem
5.4 procedural - knowledge of how to perform a sequence of operations, such as the procedure for mission analysis
5.5 strategic knowledge - techniques for how to use the various types of knowledge in solving a given problem, such as setting subgoals
5.6 explanatory - questions which are directed at the clarification of the causes of some system behavior

Information Analysis Sheet

3.0 Qualitative dimensions

3.1 Relevance - the degree to which the information retrieved satisfied the information needed by the designer

3.2 Understandability - the degree of difficulty in translating the information from the information source into the knowledge structure of the designer, measured by the difficulty or conflict in use of vocabulary, or introduction of concepts foreign to the background of the designer

3.3 Usableness in problem solution - the ease with which the information can be incorporated directly into the design, without modification or translation

3.4 Level of complexity - the subjective estimate of the number of variables or concepts and interactions which occur in the information

3.5 Precision - for data, the precision of measurement; for concepts, the closeness of match of structure

3.6 Specificity - the degree to which the context of the information matched the context of its use

3.7 Credibility - reliability and believability of the source

3.8 Needed - information required to support a design decision, for a task directly needed to solve a design problem or proceed on a solution path
APPENDIX N

PRELIMINARY INTERVIEW QUESTIONS
1. What are the design issues that manufacturers of the ATF will deal with?

2. What is the scenario the system will perform in?

3. How is the system going to be employed?

4. What it is that the user wants to do with the system?

5. (What are) the conditions under which, and basically the conditions under which he wants to do that?

6. (What is the content of the) statement of need, mission element need statement, concept of operations document?

7. (What is) the number of airplanes they expect to have in the fleet?, where they will be stationed?, the maintenance level that will be the appropriate?, logistics to be supplied?, that kind of thing.

8. Is the scenario accurate?

9. What are the functions needed to accomplish scenario?

10. What do experts say about the scenario?

11. Is our (designer's) understanding of what you are going to do with the airplane accurate?

12. (What are different) ways of doing the various things that are talked about in the scenario?

13. What is similar system and mission experts are familiar with; then, how would old system work in new mission?

14. (Would expert be interested in) concepts that we might be developing?

15. How would you (expert) want that done?

16. What (technology) is available for flying this mission?

17. When (will) those things (be) available?

18. Should we or should we not include them in our design?

19. How to shred function into finer and finer detail?
20. So the questions we ask ourselves are okay if that is what the thing has to do what are the subthings it has to do in order to do that?

21. And then what are of the sub-sub things?

22. It is a, what do we have to do in order to do that and then once that is described it's okay what do we have to do now in order to do that?

23. (A question I won't ask is)- What does it take to do that is 500 electrons running along a wire, and I do not care about that little detail?

24. When we get to that point it is time to stop asking okay what do I need to do that from a function point of view but now who shall or what shall do it?

25. The information we need but typically do not get is in the context of a cockpit what is the pilot, best able to do versus the computer?

26. If we give the pilot that function to perform what do we have available to enable him to do it?

27. So what information does a pilot need to (perform task X) release the bomb?

28. How can we implement that function if we want to give it to the pilot?

29. What hardware is available?

30. What display devices are available?

31. What algorithms are available to compute information we want to have?

32. How fast is that information updated in the computer?

33. and is that fast enough for the display to readable or usable?

34. and will the pilot get the information out of it that we want him to get?

35. How much information can we expect the operator to digest at the given chunks of time?
36. In a single seat cockpit like the TACS cockpit the problem, what you want to know is how much can this guy do?

37. So you kind of relate it to the amount of things pilots are doing now and you ask yourselves is this reasonable?

38. (Do we give it to another crew member?) and in a multi crew environment the trade off there can be add another crew member, if it turns out that for a particular series of events given the technology we picked there is more information more decisions more functions to be accomplished than we have hands and eyes to do it.

39. (To what degree can the SPO) generalize from our unique set of mission - technology - threat environment?

40. Can they (SPO) relate what we are doing to their problem?

41. How to quantify the information he needs

42. (How to) qualitatively describe it very accurately.

43. (How to know what the pilot needs to know) If something is broken in the airplane, he may need to know that, depending on how important it is.

44. (What does the pilot not need to know) Maybe he does not need to know it.

45. (What are the scenario context effects on the question answers generated by experts (pilots)?)

46. How will (the) function get accomplished?

47. Once again it is a technology search, what is in the sand box that I can choose from for presenting visual information?

48. (What is the equipment) that is going to be used to accomplish those functions?

49. (Are there) devices on the shelf and they're within some realm of compatibility with the new airplane?

50. What are the implications of such devices (e.g., for automation)?

51. What media will be used for either, for, presenting the information, is it going to be auditory, tactile, visual - that kind of thing.
52. If it is visual we are going to use a CRT or a, something else?
53. Decide how many pieces of glass you need, whether you have to have a voice system, by going back down that list of devices and allocated functions.
54. (How do we) make our work credible?
55. (How reliable are the specs contained in the design handbooks; milstd and others?)
56. (How do we develop) a confidence that what we are showing as doable in our cockpit will be doable when a manufactures get around to building the real article?

SUBJECT 02 QUESTIONS

1. (How to) redesign of the formats?
2. (What are) the implications further down?
3. Everything is interconnected so if we do this this way how is that going to work throughout the whole system?
4. (How to redo the voice system to have voice activation of format switching?)
5. Find out how someone else does it?
6. How was it done before?
7. Once we get it all on paper is to take it some pilots that we know, friendly pilots within the branch and see, if we were to do it this way does that make sense?
8. (How to track the work of other designers?)
9. (How to critique the specifics of other designer's work?)
10. (How to do variations on a checklist?)
11. Is it consistent with your emergencies as opposed to just your normal every day check list?
12. What is dependent on that?
13. (What) might not come into effect until you do a format later on down the line.
14. (How are we) going to do the everyday checklist?
15. (Step through to show) how that would work?
16. If we are going to do the emergencies, how is that going to change it?
17. (What is an example of) something that come, you might not think of it right off, but it might come into effect later on?
18. Once again, coming back to the checklist, if you have, if you are in an, what displays are going to disappear?
19. If you have 3 multi function displays and you are using, utilizing all 3 and you have an emergency what priority does an emergency override what you have up there?
20. (How to) rank the importance of things so that if you a hydraulic leak and you're in air to air combat you probably do not really care if you landing gear is not going to come down at that time?

SUBJECT 03 QUESTIONS

1. (How to have shops build a given design to specs?)
2. (What/Where are) the designs of the cockpit?
3. You know where do we put the console, cockpit, where do we have the IP, what about getting cameras for over the shoulder kind of stuff?
4. Where does this fit in (to the larger picture, e.g., format, technology, concepts, etc)?
5. When is this (equipment) coming in?
6. Is this in fact the CRT we are getting?
7. Is this in fact the CRT we are getting?
8. What are the dimensions of it?
9. Now are these dimensions the scope or is this dimension of the box?
10. If I take the box off what is the dimension of the scope?
11. What kind of stick is this?
12. What kind of buttons?
13. What are these buttons supposed to do?
14. (What is a TDC?)
15. What is the seat cover supposed to look like?
16. Who do I need to talk to about this articulating seat?
17. Where do we get this design from?
18. Where is the stick (located)?
19. (What are handbook standards or mil standards for object?)
20. (Can we meet standards?)
21. (If not) does that mean that we can not do the cockpit or do I have to change the design?
22. Come back up here and we would sit and discuss, okay what is the purpose of our cockpit?
23. If I put a 15 inches (off elbow for stick), when I start running that seat up is it going to be in a bad position?
24. Is that acceptable?
25. How would you hook up (the electronics, especially CRT)?
26. Is this analog?
27. Is this digital?
28. Is it compatible?
29. Is (this) compatible with the system that I am bringing in for the voice?
30. Have you considered how this hook is going to work?
31. Is there going to actually be an outlet that I can plug in and work?
32. Do I need a Faraday cage around each of those CRTs?
33. Do I need lead (for shielding)?
34. (What are all the other little particulars that I need to know? and where can I get that information? and from whom?)
35. (What are the) dimensions?
36. (What are the pieces of equipment available? How to get them?)
37. (What are the) space layouts and sizes?
38. (How much) access do we have?
39. (For experiments, what do) we need to do?
40. (What does) the experimenter has to be able to see?
41. Do we have visitors?
42. Are the visitors going to be in while the experiment (runs)?
43. Are we going to have experimenters or viewers at all?
44. Do we want these people in there at that time?
45. Can they just look thru the window?
46. Who can talk to who?
47. Who can not talk to who?
48. Who the pilot can only hear on these channels?
49. Do we have a off button?
50. (Do we have a) stop button?
51. Do we have issues to those natures.
52. (Do we have) safety issues?
53. What happens if something catches on fire?
54. Do I have control over all that power in the room?
55. (Do I) have to have an off button?
56. (What information do I have to have to answer these questions?)
57. (Could I get information from the SPOs and ASD/EN? What information could I get?)
58. Can we get hold of that?
59. (Can we get) briefing on it?
60. What (does SPO) have in terms of chemwear?
61. What equipment are the guys flying with?
62. (In lists of equipment) what all these numbers are?
63. (How, where, etc to procure equipment?)
64. (For interface to voice in Cockpit Natural Language study) what kind of hooks do you need from the TACS people?
65. What kind of software?
66. What kind of interfaces you have, you know, is it an RS232 bus?
67. Can you deal with an RS-232 straight out of a TI?
68. How do they want us to hook it up?
69. What words you will use to activate the switch?
70. What kind of capabilities the voice system would have?
71. (Do we have enough time to scope and implement?)
72. What limitations does the voice system have in terms of memory?
73. What can those formats do?
74. (Is it advantageous?)
75. What kind of performance measures can we get?
76. What are the optimal performance measures that we would like?
77. What can the software people record?
78. How many pilots will we need?
79. What kind of schedule should they go through?
80. Is that enough training?
81. How much training do you need from these guys?
SUBJECT 04 QUESTIONS

How some of these technologies (system automation vs manual system; touch screen; voice control; etc.) will relate to the next generation of fighter?

(What) level of automation (do) we want in cockpit?

What tasks should be done by machine and what task should be done by the human?

(What is content of) a cut and dried development of a (operational piloting) script?

What would actually be said during an actual engagement or scenario?

What areas should technologies like voice control be applied versus is HOTAS Hands on throttle and stick a better application for this task?

Is just reaching up and touching the screen a better application?

So it is kind of, it is not merely how you divide the task within the cockpit?

It is also how you mechanize those tasks,

What amount of redundancy is necessary?

(Is it) necessary to use all three of those input techniques to change a radar system or something like that?

(Are there) any differences among the various fonts that were available to use?

Was there any literature or any data to indicate that one font is better under a degraded environment than another font?

What kind of fonts if any were better than others?

Were there any differences in recognizability (of fonts)?

Would this font be acceptable to use?
(How to generate and test maximum differences?)

(What was the effect of) the size of the font?

(Is degradation of the character an important factor?)

What was the minimum update rate for the diodes under various vibratory conditions?

(What are the effects of stairstepping?)

What makes a "g" a "g" versus a "c" you know?

What the critical features were of each either symbol or alphabetic character?

(What are) recognition response times and accuracy rates on character recognition and symbol recognition?

(Are there display effects pilots can use as cues which are not overtly displayed information?)

How closely (do) you want to place those pixels?

(What are) the critical features of these symbols and alphanumeric?

(What relevant literature is out there?)

What looks interesting?

What do I reasonably feel I can get through?

(What are the constraints on us?)

What systems we thought were good candidates for some degree of automation?

What are the capabilities are in back (in the simulator)?

Who is doing what in the cockpit?

What areas should be automated and what should not?

(What and how to automate?)

(What will be pilot reluctance?)
What is usable in the cockpit?

What is feasible (in the cockpit)?

(What is optimal in the cockpit?)

(What) kind of readout you want?

(What are appropriate ways to display information?)

(How similar need training systems be to operational systems?)

How much does a pilot have to know? (in context of discussing situational awareness)

Why not take out the middle phase (in a sequence if the computer can do it)?

How much do you take away from the pilot?

How much do you still tell him?

(Out of two procedures to do things, how to tell) which way is better?

How is the computer to know?

(What is and How to do) the language definition of how the system would be interfaced to from our pilot standpoint?

And how the pilot would talk to it?

As opposed to CNL we had to deal with the fact that we had a device that had limitations and then we had to try to find out what was the best way we could interface the language to that that would give the pilot the capability to do what he wanted to, but, also given the constraints of the box that we had to deal with?

Well we had to look and see what the constraint, constraints were being, what constraints were being imposed on us by the actual devices we were integrating?
You know, how many words can be recognized at once?

Looking at subsystem selection, you know, which systems are we going to integrate?

or what how, what range of functions are we going to allow the pilot to control?

Are we going to let him do communications?
Are we going to let him do navigation?
Are we going to let him do radar management?
Are we going to let him do stores management?

Just what systems were available, subsystems were available to us?

and what could we accomplish with the technology at the time?

So interface information about how we could collect the recognition data to be able to analyze it later?

(How to) determine how accurate the devices were for that given data base?

Well things like what kind of vocabulary were we going to use?

And then we had to decide how many utterances were we going to collect?

And how many training tokens we were going to be able to provide for training purposes for each of the systems since we did not have the subjects with us?

What noise levels we were going to collect the speech data at?

How they would basically request that information or enter that information?

SUBJECT 07      SUBJECT 07

(What are) pilot type problems?

(How are they resolved?)
What is the pilot supposed to see in the cockpit to software people?

What they (formats) are supposed to be?

(What is required in a scenario to) exercise the aircraft basically?

How the formats would be used in the cockpit?

(How to) communicate this to the other people, basically all the other people that have never flown.

Does this sound reasonable to have this (design) sitting in front of a pilot?

How the formats worked?

How (do) we expect them to work?

(How to convey/understand) the overall picture of all of the formats?

How are they interrelated?

(In a point in a scenario) what the pilot is going to see next?

(What is the current state of the project at contractor change?)

(How to) put (formats) out graphically and get it off the coarse slides?

What the software people could do?

(What are) the specifics of the scenario we were going to work with, type of scenarios, battle scenarios, combat time, combat experience?

What are fighter tactics?

What are fighter groups?

(What is) fighter pilot's language?

Can we do it (create the scenario) during the time allowed?

is each segment of this scenario realistic?
Is it feasible that they do this on a mission? 
what would they do on these missions? 
What do they do on the ground? 
What do they do after take off? 
What would they do on each one of those (three or four variants of the mission)?

(When working) in the format area, (how) some buttons would affect all the other formats?

One of the original questions was what does the pilot want to see where?

what if you are going into battle and something happens - you are making your strafing run now and your engine goes out?

As you punch the buttons, do you care?

(How to know and how to do) to prioritize something and sometimes a pilot will want to see it right away and some times he won't

(How to) redevelop it (baseline scenario) to match our hardware here?
APPENDIX O

DIARY PAGE SAMPLE

This appendix contains three xeroxed pages from the design diary of one designer.
11/17/87, 16:00 - 16:25
- Me
- Determining times
  (minimum update &
  maximum response)
  for switches in TACS
- F-18 Human Engin. Crew
  Station Design Doc.
- F-15 Human Engin. Design
  Appr. Document-Operator
- H.E. Guide to Equip. Design

(previous to 11-17-87
time spent approx. 3 to 4 hours)
11/18/82 , 10:00 - 11:15
- me
- determining times for
  switches in TACS
  cockpit (see 11-17)

- Human Factors Journal
- MIL STD 1472
- MIL STD USER/COMPUTER
  INTERFACE
  15 - 16:30
- end of day → Pete Levering
  involved
11-19-87 / 10:00-11:00
/ HOUR

- me, J. Kovacs, J. Upshaw.
- determining R&D delta collection
- procedures and potential
- capabilities for experiment
- tests console.

Sources
* Advanced Crew Station Concepts
  Air-to-air Fighter
  Air Force Technical Report
  (AFWAL-TR-84-3055)

* MER / Singer Link Test Plan
  For TERRAIN FOLLOWING DISPLAY
  TEST PLAN.
APPENDIX P

TRANSCRIPTION SUPPORT TOOL

This appendix is the list of domain words created ad hoc to help the transcriber understand the tapes of interviews and integration meetings.
TRANSCRIPTION SUPPORT TOOL

USE LIST OF ACTIVE WORDS, AND FDL TERMINOLOGY FROM PRELIMINARY TRANSCRIPTS.

This is designed to make the transcriber's job easier and to reduce the number of errors made in transcription.

allocate  multipurpose displays
analogy  ownership radar
analysis  ownership sensors
assign  parameter
assumption  physiological
ATF - advanced tactical fighter  presumption
automation  Fk probability of kill
baseline  Ps prob. of survival
beyond visual range (BVR)  remode
cuff  reticle
checklist  ripple effect
cockpit geometry  SON
compatibility  SWAT
contingencies  symbologies
C-5  TAC
CRT - cathode ray tube  TACS
cue  techniques

design concept  traceability
design criteria  variable
design decision  within visual range
design handbook
design issue
digital terrain map
e xtrapolate  EXTRADAP
F-15  TACTICAL DISPLAY SYSTEM
F-16  TACTICAL INFORMATION PROCESSOR
function  TACAIR
high acceleration cockpit  methodology
HMD - helmet mounted display  mission
HOTAS - hands on throttle and stick  mission analysis
HUD - heads up display  mission characterization
hypervelocity  mockup
implication  mode
MACAIR  modify
methodology
mission
mission analysis
mission characterization
APPENDIX Q

INTEGRATION MEETING TRANSCRIPT SAMPLE

Two pages of integration meeting transcripts are provided, to show the format into which the tapes were transcribed, and to provide a typical dialogue example.
When you put determine and/or set on the same line you are doing two different functions.

Right?

S12

That is right.

Make it just want to determine, go through your determines first.

S01

Yea.

The set thing would be part of correct to desired down at 1400.

S12

I agree.

S01

The set part of all that.

Once again it is determine desired state.

The four biggies on this page.

Sense present state.

Determine deviations.

Correct.

Right?

E

1400 can say something like set to desired or ... well.

S01

And four is the action part of this, the first three are all computational kinds of things just to draw distinction for no particular reason.

S12
What do I have?
What do I want?
What is the difference?

S01

So this thing that we are working on determine and/or set.
The set part ... well.
Determine.
Seems to me the setting what you want it to be is part of four.

Or 14 or 4 million.
Anybody agree with that?
E
Yea.

S04

What if set is...

S01

See what we are doing here, we will go back to the scheme of things.
Let's assume for a moment that the top four levels are accurate.
In order to control the vehicle you have got to determine what state it is in.
You have to to decide what it should be in.
You have to see if there is any difference.
And then you have got to make the change.
E
You have to do 8 control actions whether that is set or reset.
APPENDIX R

FIELD NOTEBOOK SAMPLE

Three pages of the field notebook are provided to illustrate the type of notes kept by the investigator.
FIELD NOTEBOOK SAMPLE

4/13/07

MRS. MADDEN/20TH BN/LENNAN/KUNKEL/BRANT/ALLANKO

- ? Func1, no organization.
  - Commerce. Money, Thieves / Intruders.
  - Into Lower Stores

- Miss Last Room - Continuation Gap -
  Stands on top.


MRS. MADDEN -> SCHANTZO ->

E30 @ 1:30 PM. Summon CHINCH.

Carded Tablet, M8 w/1:30 cards, 22.
Four new Solutions - not functions

M�6L / Frych - across the function auditors.
M6T, 156. Preparedness, 06. Auditors. 10
Bottom: Concept: -> 150.
Outputs - Task Allocation / Risk
Support / Information Requirements
Pillow and Object to Approve

200
Traces: Aero Industry

Consider the following:

- What are the relevant factors that contribute to the
  project's success?
- What are the potential risks and how can they be
  mitigated?
- How will the project impact the environment?

In summary, this project has potential to be successful
but requires careful consideration of various factors.

Field Notebook Sample
FIELD NOTEBOOK SAMPLE

[Handwritten diagram with various text and symbols]
APPENDIX S
INTERACTION ANALYSIS INSTRUCTIONS
INTERACTION ANALYSIS INSTRUCTIONS

Four passes were required through the meeting transcripts to complete the interaction analysis. The first pass was to edit the transcript and insert subject identifiers by reviewing the hard copy and listening to the tape from which it originated. The second pass was used to mark implicit and explicit questions, and to familiarize the investigator with the subject matter in a more connected way than was possible when editing. Categories of question types were tentatively generated with respect to the problem solving behavior of the group. The third pass segmented the conversation into clusters of questions and other statements on related topics. The fourth pass examined clusters for patterns of question asking behavior and errorful behavior. Notes were recorded directly on the transcripts themselves, and were reviewed periodically as the investigator gained more knowledge of the domain and the design process.

Read the statement example sheets and the glossary definitions. Keep these available as a reference while doing the coding.
APPENDIX T
SAMPLE CONCEPT MAPS
APPENDIX U

TACS FUNCTION ANALYSIS

The function analysis work was the place where short term memory problems occurred. This is the final document produced by that work.
FIGHTER COCKPIT FUNCTIONS

1000000 MANAGE RESPONSE TO TARGET(S) (Having to do with the selection of targets and the control of devices used to damage or destroy them.)

1100000 SEARCH

1110000 DETECT active TARGET(S)
(M/A) 1111000 DETECT PATTERNS of electromagnetic energy

(M/A) 1112000 TRANSFORM and FILTER PATTERNS of electromagnetic energy

(A) 1113000 TRANSMIT electromagnetic ENERGY

1120000 DETECT passive TARGET(S)

(M/A) 1121000 DETECT PATTERNS of electromagnetic energy

(M/A) 1122000 TRANSFORM and FILTER PATTERNS of electromagnetic energy

(A) 1123000 TRANSMIT electromagnetic ENERGY

1200000 DETERMINE RESPONSE to tgt(S)

1210000 IDENTIFY TARGET(S)

(M/A) 1211000 SORT TARGET(S)

(M/A) 1212000 DETERMINE TARGET CATEGORY (Compare received tgt information to stored tgt information.)

(M/A) 1212100 DETERMINE source of tgt (surface, air, space)

(M/A) 1212200 DETERMINE range & bearing of tgt

(M/A) 1212300 DETERMINE altitude and velocity of tgt

(M/A) 1212400 DETERMINE type of sensor

(M/A) 1212500 DETERMINE name of tgt

(M/A) 1212600 DETERMINE unfriendly, unknown, friendly status of tgt

(A) 1212700 DETERMINE lethality envelope

(M/A) 1220000 DETERMINE tgt PRIORITY (ies)

(M/A) 1230000 DETERMINE tgt ASSIGNMENT(S)

1300000 EXECUTE RESPONSE to tgt(S(s))

1310000 PREPARE WEAPONS

(M/A) 1311000 DETERMINE weapon INVENTORY and STATUS (type, quantity, location, status)

(M/A) 1312000 DETERMINE TARGET INFORMATION (type, location, constraints,...)

(M/A) 1313000 DETERMINE best weapon OPTION(S)

(M/A) 1314000 CONFIGURE WEAPON SYSTEM (fuse setting, delivery mode, interval, quantity, status (standby, armed, etc.)

(M/A) 1315000 CONSENT (if appropriate), arm weapons

(M/A) 1320000 DETERMINE MANEUVERS & CONFIGURATIONS w/resp to terrain, employment tactics, time on threats, wpn type, time to detonation, safe esc dist, (To 3140000)

(M) 1330000 EXECUTE WEAPONS

1340000 PROVIDE WEAPON GUIDANCE

(H/A) 1341000 TRANSMIT EOM ENERGY for tgt Lock-on

(A) 1342000 DETECT electromagnetic ENERGY

(A) 1343000 DETERMINE weapon guidance SOLUTION

(A) 1344000 TRANSMIT weapon guidance INFORMATION

1400000 DETERMINE DAMAGE to tgt(S)

1410000 SEARCH and DETECT "ACTIVE AND PASSIVE" TARGETS

(H/A) 1411000 TRANSMIT electromagnetic energy if required

(H/A) 1412000 DETECT PATTERNS of electromagnetic energy

(H/A) 1413000 RECEIVE, TRANSFORM AND FILTER those patterns of electromagnetic energy
2000000 MANAGE RESPONSE TO THREAT(S) (Having to do w/the protection of the system from entities which have the potential for preventing mission completion

2100000 DETERMINE EXISTENCE OF THREAT(S)
2110000 DETECT THREAT(S)
(M/A) 2111000 DETECT PATTERNS of electromagnetic energy
(M/A) 2111100 TRANSFORM patterns of electromagnetic energy
2112000 FILTER patterns of electromagnetic energy
(M/A) 2112100 DETECT all OBSTRUCTIONS to projected flight path and compare to expected (transmitting and receiving energy)
(M/A) 2112200 DETECT all items closing aircraft (transmitting and receiving energy)
(M/A) 2112300 DETECT levels of chemical, biological, and radiological AGENTS
(M/A) 2120000 RECALL briefed THREATS
2200000 DETERMINE RESPONSE(S) to threat(s)
2210000 DETERMINE THREAT CATEGORY(S) (compare for match w/template stored threat
(M/A) 2211000 DETERMINE source of threat(s) (surface, air, space)
(M/A) 2212000 DETERMINE type of sensor (active/passive/visual/R.F./I.R./audio/laser)
(M/A) 2213000 DETERMINE type of delivery (stationary/self-propelled/ballistic/energy beam)
(M/A) 2214000 DETERMINE type of guidance (terminally guided, ballistic, remote)
(A) 2215000 DETERMINE velocity
(M/A) 2216000 DETERMINE name of threat
(M/A) 2221700 DETERMINE unfriendly, unknown, friendly
2220000 COMPAR program LEVEL of detected threat with acceptable level
(A) 2221000 DETERMINE LETHALITY ENVELOPE
(A) 2222000 DETERMINE RANGE and TIME-TO-GO
2230000 DETERMINE PRIORITY
(M/A) 2231000 DETERMINE threat INTENTION(S)
2232000 PREDICT threat(s) PROGRESS
(M/A) 2233000 DETERMINE relative threat(s) LETHALITY
2240000 DETERMINE METHODS to respond to threat(s)
2241000 DETERMINE COUNTER MEASURES to negate threat(s) (To 3130000)
(M/A) 2241100 EXECUTE electromagnetic DECEPTION (EOM, IFF, Jamming)
2241200 EXECUTE physical DECEPTION (To 3130000)
(M/A) 2241210 EXECUTE MANEUVERING (Methods that avoid or maneuver away from threat(s)
(H/A) 2241220 EXECUTE Expendables (Chaff, Flares)
(H/A) 2242000 DETERMINE WEAPON to negate threat
(H/A) 2250000 DETERMINE or RECALL set of METHODS to respond to threats by determining combinations countermeasures and weapons that best counter threat(s)
3000000 CONTROL VEHICLE (Having to do with establishment of location, orientation and/or motion of the vehicle in space)

3100000 DETERMINE desired aircraft STATE within acceptable ranges

3110000 DETERMINE desired aircraft ORIENTATION

3111000 DETERMINE desired PITCH
3112000 DETERMINE desired YAW
3113000 DETERMINE desired ROLL

3120000 DETERMINE desired ALTITUDE

(M/A) 3121000 DETERMINE desired ALTITUDE w/ respect to the surface

(M/A) 3122000 DETERMINE desired ALTITUDE w/ respect to MSL

(M/A) 3123000 DETERMINE desired RATE of CHANGE of ALTITUDE

3130000 DETERMINE desired THRUST SETTING

3131000 DETERMINE desired VELOCITY
3132000 DETERMINE desired RATE OF CHANGE of VELOCITY
3133000 DETERMINE desired THRUST DIRECTION (Up, Down, Fwd, Aft)

3140000 DETERMINE desired CONFIGURATION [INFORMATION]

3141000 DETERMINE desired STATUS OF WEAPONS
3142000 DETERMINE desired STATUS OF LIFT DEVICES
3143000 DETERMINE desired STATUS OF DRAG DEVICES
3144000 DETERMINE desired STATUS OF EXTERNAL FUEL TANKS
3145000 DETERMINE desired STATUS OF LANDING GEAR
3146000 DETERMINE desired STATUS OF CENTER-OF-GRAVITY
3147000 DETERMINE desired STATUS OF INFLIGHT REFUELING DOOR
3148000 DETERMINE desired STATUS of THRUST-CONTROLLING DEVICES

3200000 DETERMINE present aircraft STATE

3210000 DETERMINE present aircraft ORIENTATION

3211000 DETERMINE present PITCH
3212000 DETERMINE present YAW
3213000 DETERMINE present ROLL

3220000 DETERMINE present ALTITUDE

(M/A) 3221000 DETERMINE present ALTITUDE w/ respect to surface

(M/A) 3222000 DETERMINE present ALTITUDE w/ respect to MSL

(M/A) 3223000 DETERMINE present RATE OF CHANGE of ALTITUDE

3230000 DETERMINE present THRUST SETTING

3231000 DETERMINE present VELOCITY
3232000 DETERMINE present RATE OF CHANGE of VELOCITY
3233000 DETERMINE present THRUST DIRECTION (Up, Down, Fwd, Aft)

3240000 DETERMINE present CONFIGURATION [INFORMATION]

3241000 DETERMINE present STATUS of WEAPONS
3242000 DETERMINE present STATUS of LIFT DEVICES
3243000 DETERMINE present STATUS of DRAG DEVICES
3244000 DETERMINE present STATUS of EXTERNAL FUEL TANKS
3245000 DETERMINE present STATUS of LANDING GEAR
3246000 DETERMINE present STATUS of CENTER-OF-GRAVITY
3247000 DETERMINE present STATUS of INFLIGHT REFUELING DOOR
3248000 DETERMINE present STATUS of THRUST-CONTROLLING DEVICES

3300000 DETERMINE DEVIATION from desired aircraft STATE

3310000 COMPARE desired and present aircraft ORIENTATION

3311000 COMPARE desired and present PITCH
3312000 COMPARE desired and present YAW
3313000 COMPARE desired and present ROLL
3320000 COMPARE desired and present ALTITUDE
(M/A) 3321000 COMPARE desired and present ALTITUDE w/respect to surface
(M/A) 3322000 COMPARE desired and present ALTITUDE w/respect to MSL
(M/A) 3323000 COMPARE desired and present RATE of CHANGE of ALTITUDE
3330000 COMPARE desired and present THRUST SETTING
3331000 COMPARE desired and present VELOCITY
3332000 COMPARE desired and present RATE-of-CHANGE of VELOCITY
3333000 COMPARE desired and present THRUST DIRECTION (Up, Down, Fwd, Aft)
3340000 COMPARE desired and present CONFIGURATION [INFORMATION]
3341000 COMPARE desired and present STATUS of WEAPONS
3342000 COMPARE desired and present STATUS of LIFT DEVICES
3343000 COMPARE desired and present STATUS of DRAG DEVICES
3344000 COMPARE desired and present STATUS of EXTERNAL FUEL TANKS
3345000 COMPARE desired and present STATUS of LANDING GEAR
3346000 COMPARE desired and present STATUS of CENTER-of-GRAVITY
3347000 COMPARE desired and present STATUS of INFLIGHT REFUELING DOOR
3348000 COMPARE desired and present STATUS of THRUST-CONTROLLING DEVICES
3400000 CORRECT to desired aircraft STATE
3410000 MODIFY aircraft ORIENTATION
3411000 MODIFY PITCH
3412000 MODIFY YAW
3413000 MODIFY ROLL
3420000 MODIFY ALTITUDE
3421000 MODIFY ALTITUDE w/respect to surface
3422000 MODIFY ALTITUDE w/respect to MSL
3423000 MODIFY RATE of CHANGE of ALTITUDE
3430000 MODIFY THRUST SETTING
3431000 MODIFY VELOCITY
3432000 MODIFY RATE-of-CHANGE of VELOCITY
3433000 MODIFY DIRECTION (Up, Down, Fwd, Aft)
3440000 MODIFY CONFIGURATION [INFORMATION]
3441000 MODIFY STATUS of WEAPONS
3442000 MODIFY STATUS of LIFT DEVICES
3443000 MODIFY STATUS of DRAG DEVICES
3444000 MODIFY STATUS of EXTERNAL FUEL TANKS
3445000 MODIFY STATUS of LANDING GEAR
3446000 MODIFY STATUS of CENTER-of-GRAVITY
3447000 MODIFY STATUS of INFLIGHT REFUELING DOOR
3448000 MODIFY STATUS of THRUST-CONTROLLING

4000000 NAVIGATE (Having to do with the definition of the location and the dest of the vehicle and the definition of the path from location to dest.)
4100000 DETERMINE desired PATH and SCHEDULE from point of departure to destination
(M/A) 4110000 DETERMINE the POINTS of dep and dest(s), on a common coord sys
(M/A) 4120000 DETERMINE the TIME of arrival for destination(s)
(M/A) 4130000 DETERMINE AREAS on the coord sys, where it is best not to go due to
threats, laws, rules, wx, system limitations

(M/A) 4140000 DETERMINE AREAS to maneuver or hold to await go-ahead or to meet schedule

(M/A) 4150000 DETERMINE alt PATHS that connect the dep & dest pts considering constraints above

(M/A) 4160000 DETERMINE alt SCHEDULES that connect the dep & dest pts considering constraints above

4200000 DETERMINE PRESENT acft STATE w/resp. to path and schedule

4210000 DETERMINE present acft POSITION relative to the world or some obj

(A) 4211000 DETERMINE BEARING, DISTANCE, and ELEVATION angle to some pt on the world or any detectable obj (moving or stationary, on the surface, or in the air

(A) 4212000 DETERMINE ALTITUDE (w/resp to sea level, surface)

(A) 4213000 DETERMINE POSITION (relative to some known point)

4220000 DETERMINE PRESENT acft VELOCITY rel. to the world, or other obj

(A) 4221000 DETERMINE SPEED (w/resp. to a pt on the world, to air)

(A) 4222000 DETERMINE DIRECTION w/resp. to a common coord sys magnetic field

(A) 4230000 SENSE PRESENT TIME (real and elapsed time, time-to-go)

4300000 DETERMINE DEVIATION(S) between present & planned state w/respect to path and schedule

4310000 COMPARE PRESENT PATH with planned path

4320000 COMPARE PRESENT VELOCITY w/planned velocity

4330000 COMPARE PRESENT TIME w/planned time.

4340000 COMPARE PRESENT ACCELERATION w/planned acceleration

4400000 DETERMINE ALTERNATIVE PATH(S) and SCHEDULE(S) to achieve men

4410000 DETERMINE OPTIMUM PATH & SCHEDULE from point of departure, to destination

4411000 DETERMINE the POINT of DEPARTURE, the destination(s), on a common coordinate system

4412000 DETERMINE TIME of arrival at destination(s)

4413000 DETERMINE AREAS on the coord. sys. where it is best not to go due to threats, law, rules, wx, subsystems limitations

4414000 DETERMINE AREAS to maneuver, or hold to await, go-ahead, or meet schedule

4420000 SELECT OPTIMUM PATH & SCHEDULE from pt of departure, to destination, and return

4421000 DETERMINE alt PATHS that connect the departure, destination, considering the areas described above

4422000 DETERMINE ALT. SCHEDULES that connect the departure, destination, considering the areas described above

4500000 DETERMINE WHICH IS BETTER: (Either)

- MAINTAIN present PATH AND SCHEDULE..(or)
- EXECUTE a new PATH AND SCHEDULE... (either pioneer or correction to planned)

4510000 DETERMINE man COSTS of ALTERNATIVE SOLUTIONS to achieve desired path & schedule

4520000 COMPARE man COSTS of ALTERNATIVE SOLUTIONS to achieve desired path & schedule

4600000 EXECUTE DECISION (CONTROL VEHICLE)
500000 MANAGE COMMUNICATIONS (Having to do with the receipt and transmission of information originating from or being sent to entities outside the vehicle. Includes directly sensed energy

5100000 RECEIVE COMMUNICATIONS

(H/A) 5110000 DETECT PATTERNS of ENERGY
(H/A) 5120000 AMPLIFY PATTERNS of ENERGY
(H/A) 5130000 FILTER PATTERNS of ENERGY
(H/A) 5140000 TRANSDUCE received PATTERNS of ENERGY
(H/A) 5150000 DECODE as necessary
(H/A) 5151000 COMPARE PATTERNS of received ENERGY to known patterns
(H/A) 5152000 TRANSLATE from received pattern to desired pattern
(H/A) 5153000 DETERMINE CONTEXT of received MESSAGE
(H/A) 5160000 VERIFY accuracy of received patterns of energy
(H/A) 5161000 COMPARE received PATTERNS to known and expected patterns
(H/A) 5162000 COMPARE meaning of patterns to expected context
(H/A) 5163000 AUTHENTICATE

5200000 SEND COMMUNICATIONS

(H/A) 5210000 DETERMINE INFORMATION to be transmitted
(H/A) 5211000 COMPARE maintenance INFORMATION
(H/A) 5212000 COMPARE intelligence DATA (OPS, EOB, damage assessment, etc.)
(H/A) 5213000 COMPARE request for INFORMATION
(H/A) 5214000 COMPARE flight profile INFORMATION (Wx, refuel, status, posit.)
(H/A) 5220000 DETERMINE direction, frequency, power and timing of transmission
(H/A) 5221000 DETERMINE intended RECEIVER
(H/A) 5222000 DETERMINE LOCATION and RANGE of intended receiver
(H/A) 5223000 DETERMINE transmission CONSTRAINTS based upon information from threat management
(H/A) 5224000 DETERMINE FREQUENCY, DIRECTION, POWER, AND TIMING considering vulnerability induced by transmission and probability
(H/A) 5230000 ENCODE
(H/A) 5231000 DETERMINE CODE intended receiver is expecting
(H/A) 5232000 TRANSLATE MESSAGE with code
(H/A) 5240000 ENTER INFORMATION for transmission
(H/A) 5250000 TRANSMIT communication(s)

600000 MAINTAIN LIFE SUPPORT

6100000 DETECT environmental STATE
(M) 6110000 DETECT PRESSURE
(M/A) 6120000 DETECT G's
(M/A) 6130000 DETECT TEMPERATURE
(M/A) 6140000 DETECT CBR ENTITIES (XRay, Gamma, Neutron, Proton, etc.)

(M/A) 6150000 DETECT VISUAL IMPEDIMENTS (Electromagnetic, etc.)
(M/A) 6160000 DETECT OXYGEN LEVEL

6200000 RECALL acceptable LEVELS of environmental STATE

6300000 COMPARE detected STATE w/acceptable levels

(M) 6310000 COMPARE Detected PRESSURE w/acceptable pressure
(M/A) 6320000 COMPARE Detected G's with acceptable level of G's
(M/A) 6330000 COMPARE Detected TEMPERATURE w/acceptable temperature

(M/A) 6340000 COMPARE Detected CBR ENTITIES (XRay, Gamma, Neutron, Proton, etc. w/acceptable CBR entities
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(6/A) 6350000 COMPARE Detected VISUAL IMPEDIMENT (Electromagnetic, etc.)
(6/A) 6360000 COMPARE Detected OXYGEN LEVEL w/required oxygen level
6400000 DETERMINE RESPONSE to unacceptable levels
(6/A) 6410000 DETERMINE RESPONSE(S) (Adaptive Actions/Egress)
(6/A) 6420000 COMPARE alternative RESPONSES
6500000 EXECUTE RESPONSE (Adaptive Actions/Egress)

7000000 MANAGE TRAINING
7100000 PROVIDE for the MAINTENANCE of KNOWLEDGE/SKILLS
(6/A) 7110000 PRACTICE
(6/A) 7120000 TEST
7200000 PROVIDE for the MAINTENANCE of KNOWLEDGE/SKILLS
(6/A) 7210000 PRACTICE
(6/A) 7220000 TEST

8000000 MANAGE SUBSYSTEMS (Having to do w/the monitoring, controlling, & maintaining of vehicle components
8100000 DETECT operating STATE(S)
(6/A) 8110000 DETECT TARGET-MANAGEMENT present operating STATE
(6/A) 8120000 DETECT THREAD-MANAGEMENT present operating STATE
(6/A) 8130000 DETECT VEHICLE CONTROL present operating STATE
(6/A) 8140000 DETECT NAVIGATION present operating STATE
(6/A) 8150000 DETECT COMMUNICATION present operating STATE
(6/A) 8160000 DETECT other SUB-SYSTEMS present operating STATE
(6/A) 8170000 DETECT TRAINING operating STATE
(6/A) 8180000 DETECT LIFE SUPPORT operating STATE
(6/A) 8200000 RECALL desired operating STATE
(6/A) 8210000 RECALL desired TARGET-MANAGEMENT operating STATE
(6/A) 8220000 RECALL desired THREAD-MANAGEMENT operating STATE
(6/A) 8230000 RECALL desired VEHICLE CONTROL operating STATE
(6/A) 8240000 RECALL desired NAVIGATION operating STATE
(6/A) 8250000 RECALL desired COMMUNICATION operating STATE
(6/A) 8260000 RECALL desired other SUB-SYSTEMS operating STATE
(6/A) 8270000 RECALL desired TRAINING operating STATE
(6/A) 8280000 RECALL desired LIFE SUPPORT operating STATE
8300000 COMPARE DETECTED and DESIRED operating STATE
(6/A) 8310000 COMPARE present with desired TARGET-MANAGEMENT operating STATE
(6/A) 8320000 COMPARE present with desired THREAD-MANAGEMENT operating STATE
(6/A) 8330000 COMPARE present with desired VEHICLE CONTROL operating STATE
(6/A) 8340000 COMPARE present with desired NAVIGATION operating STATE
(6/A) 8350000 COMPARE present with desired COMMUNICATION operating STATE
(6/A) 8360000 COMPARE present with desired other SUB-SYSTEMS operating STATE
(6/A) 8370000 COMPARE present with desired TRAINING operating STATE
(6/A) 8380000 COMPARE present with desired LIFE SUPPORT operating STATE
8400000 DETERMINE RESPONSE to deviations from desired operating state
8410000 DETERMINE possible RESPONSE to deviations from desired operating state
8420000 COMPARE possible RESPONSES to deviations from desired operating states
8500000 EXECUTE RESPONSE
8510000 EXECUTE CHANGES in operating state
8520000 STORE DISCREPANCIES for follow-up maintenance
NOTE: Operating parameters (STATES) have values that are sometimes constant, absolute, variable with respect to rate of change types; the point is that the parameters are not always fixed value.

9000000 PILOT DECISION MAKING (Having to do w/the selection of alternative courses of action, the accomplishment of which results in the desired solution or outcome)

9100000 RECEIVE INFORMATION from other functions
(M) 9110000 RECEIVE INFORMATION w/respect to tgts
(M) 9120000 RECEIVE INFORMATION w/respect to threats
(M) 9130000 RECEIVE INFORMATION w/respect to controlling vehicle
(M) 9140000 RECEIVE INFORMATION w/respect to navigation
(M) 9150000 RECEIVE INFORMATION w/respect to communications
(M) 9160000 RECEIVE INFORMATION w/respect to maintaining life support
(M) 9170000 RECEIVE INFORMATION w/respect to training
(M) 9180000 RECEIVE INFORMATION w/respect to managing subsystems

9200000 PROCESS INFORMATION

9210000 RECALL decision-making rules
(M) 9211000 PROCESS INFORMATION w/respect to tgts
(M) 9220000 PROCESS INFORMATION w/respect to threats
(M) 9230000 PROCESS INFORMATION w/respect to controlling vehicle
(M) 9240000 PROCESS INFORMATION w/respect to navigation
(M) 9250000 PROCESS INFORMATION w/respect to communications
(M) 9260000 PROCESS INFORMATION w/respect to maintaining life support
(M) 9270000 PROCESS INFORMATION w/respect to training
(M) 9280000 PROCESS INFORMATION w/respect to managing subsystems

9300000 DECIDE course-of-action

9400000 SEND INFORMATION to other functions
(M) 9410000 SEND INFORMATION w/respect to tgts
(M) 9420000 SEND INFORMATION w/respect to threats
(M) 9430000 SEND INFORMATION w/respect to controlling vehicle
(M) 9440000 SEND INFORMATION w/respect to navigation
(M) 9450000 SEND INFORMATION w/respect to communications
(M) 9460000 SEND INFORMATION w/respect to maintaining life support
(M) 9470000 SEND INFORMATION w/respect to training
(M) 9480000 SEND INFORMATION w/respect to managing subsystems


Miyake, N. and Norman, D.A. (1979). To ask a question, one must know enough to know what is not known. Journal of Verbal Learning and Verbal Behavior, 18, 357-364.


