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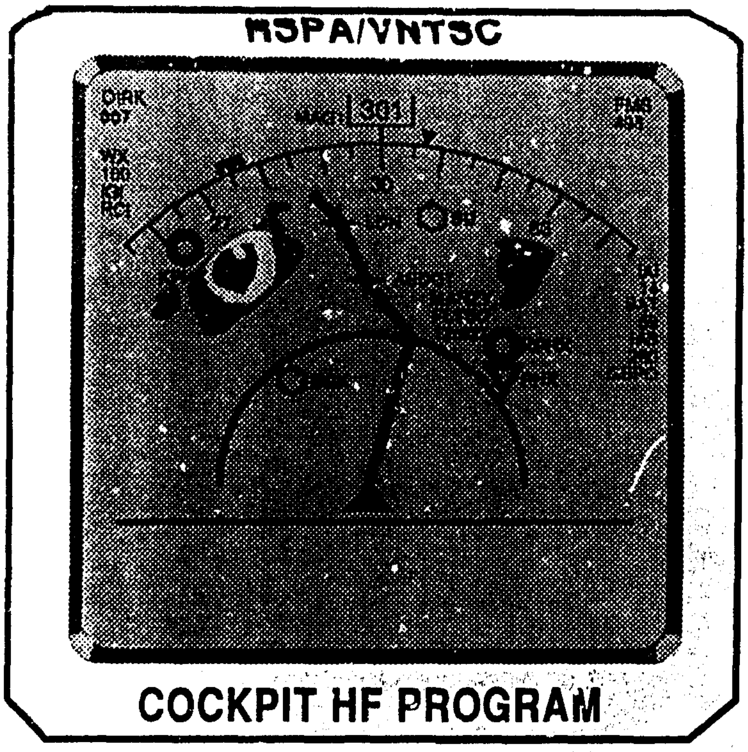
Key Cognitive Issues in the Design of Electronic Displays of Instrument Approach Procedure Charts



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13. ABSTRACT (Maximum 200 words)

This report provides a general introduction to the field of cognitive psychology and the application of well researched cognitive issues to the design of electronic instrument approach procedures (EIAP) displays. It presents 46 cognitive issues and 108 design principles. Its basic premise is a recognition of the need for the pilot to get unambiguous information as quickly and easily as possible in such a way that it can be remembered until the time that it must be used. Recognition and discriminability of patterns, stress resulting from heavy workload, the effects of divided attention, and the need to take account of the pilot's expectations are discussed. The merits of color and size, paper and electronic display, and temporary removal of nonessential information are examined. Among the conclusions made by the report are recommendations for more investigation in the following areas: symbol design, grouping and coding of information, orientation and scaling of information, control of clutter, and ways of overcoming the harmful effect of interruptions to attention or to performance of sequential actions.

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PREFACE

This report presents key cognitive issues that should be addressed in the design and evaluation of electronic display formats used to depict instrument approach procedures (EIAP). It is based on a comprehensive review of cognitive psychology literature. For each cognitive issue, design guidelines and the relevance of the guidelines to EIAP design are presented. This report is submitted by Monterey Technologies, Inc. under a contract with Battelle (Subcontract No. 38125(4529)-2183) to develop a cognitive handbook of design guidelines for designers and evaluators of EIAPs. Dr. Michael McCauley served as the Program Manager for Monterey Technologies, Inc. His contributions and those from Mr. Donald Vreuls and Dr. Barry H. Beith are appreciated by the author. The first step of the project involved studying the instrument approach task to determine the cognitive skills required for the task. The second step was to identify the key cognitive issues and consider their relevance for EIAP design guidelines.

This project is part of a continuing effort at the Volpe National Transportation Systems Center to develop human factors design guidelines for electronic depiction of instrument approach procedures. Dr. M. Stephen Huntley directed this research for the Volpe Center. Mr. Donald Eldredge of Battelle acted as Program Manager for Battelle. Both Dr. Huntley and Mr. Eldredge provided support and guidance throughout the project. Their contributions of knowledge of the instrument approach task and related human factors issues were greatly appreciated.

This work was funded by the Human performance Program in the FAA's Research and Development Service as part of their cockpit human factors research.

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2 = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2 = 0.09 square meter (m_2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectares (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = v °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yeards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
1 hectare (he) = 10,000 square meters (m^2) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliters (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH-CENTIMETER LENGTH CONVERSION

INCHES	0	1	2	3	4	5	6	7	8	9	10

CENTIMETERS: 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 25.40

QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10286.

TABLE OF CONTENTS

Section			Page
1.	INTRODUCTION		1
	1.1	Background	1
	1.2	Cognitive Psychology	1
	1.3	Cognitive Skills Required for the Approach Task	2
	1.4	Theories	3
2.	MEMORY CONSIDERATIONS		7
	2.1	Sensory Storage	7
	2.2	Working Memory	7
	2.3	Long-Term Memory	8
	2.4	Imagery and Visual Memory	9
3.	PERCEPTION AND COGNITION		11
	3.1	Visual Search	11
	3.2	Pattern Recognition	12
	3.3	Mental Rotation	13
	3.4	Display Clutter	14
4.	ATTENTION AND PERFORMANCE LIMITATIONS		17
	4.1	Focused Attention	17
	4.2	Selective Attention	17
	4.3	Divided Attention	18
	4.4	Workload Effects	19
	4.5	Depth of Processing: Controlled vs. Automatic	21
	4.6	Time-Sharing and Resource Competition	22
	4.7	Stress Effects	23
	4.8	Errors (Skill-Based)	24
5.	KNOWLEDGE		27
	5.1	Mental Models	27
	5.2	Implicit vs. Explicit	28
	5.3	Situation Awareness	29
	5.4	Mental Maps and Navigation	29
6.	PROBLEM SOLVING AND REASONING		31
	6.1	Reasoning	31
	6.2	Decision Making	32
	6.3	Heuristics	33
	6.4	Biases	34
	6.5	Errors--Rule-Based and Knowledge-Based	35

Section		Page

6.6 Effects of Interruptions 36
6.7 Planning 37
6.8 Mental Arithmetic 38

7. ORGANIZATION AND GROUPING OF INFORMATION 41

7.1 Categorizing Information 41
7.2 Proximity 41
7.3 Similarity and Coding 42
7.4 Continuity and Closure 43
7.5 Consistency 44
7.6 Layering 44

8. DIRECT PERCEPTION AND INTEGRATION OF INFORMATION 47

8.1 Symbols 47
8.2 Population Stereotypes 48
8.3 Cognitive Tasks 49
8.4 Display Aircraft Location 49

9. CODING 51

9.1 Symbols/Shape 51
9.2 Size 52
9.3 Color 53
9.4 Other Methods 55

10. DISPLAY OF TERRAIN INFORMATION 57

11. LANGUAGE CONSIDERATIONS 59

12. DYNAMIC DISPLAYS 61

12.1 North Up vs. Track Up 61
12.2 Pilot Control of Displays 62

13. CONCLUSIONS AND RECOMMENDATIONS 65

14. REFERENCES 67

APPENDIX. Summary of Current Practices, Operational Requirements and Potential Cognitive Implications A-1

LIST OF FIGURES

Figure		Page
A-1.	Initial CGS of Instrument Approach Task	A-27
A-2.	CGS of ILS Approach	A-30

LIST OF TABLES

Table		
1.	Mean Detection Time for Targets in Williams' Visual Search Experiment	51
2.	Comparison of Electronic Cockpit and Cartographical Color Conventions	54
A-1.	Information Requirements for the IAP Task	A-13

LIST OF ACRONYMS

ACARS	automatic communication and reporting systems
ADF	automatic direction finders
ATC	air traffic control
CGS	conceptual graph structure
CRT	cathode ray tube
DH	decision height
DME	distance measuring equipment
EIAP	electronic instrument approach procedure
ELS	electronic library system
FMS	flight management systems
GNSS	Global Network Satellite System
HSI	horizontal situation indicator
IAP	instrument approach procedure
IAPC	instrument approach procedure chart
IFR	instrument flight rules
ILS	instrument landing systems
MDA	minimum descent altitude
NAVAID	navigational aid
NDB	non-directional beacon
NOS	National Ocean Service
SATCOM	Satellite Communications
SID	standard instrument departure
SME	subject matter experts
STAR	standard terminal arrival routes
VOR	very high frequency omnidirectional range

1. INTRODUCTION

A disproportionately large number of aircraft accidents, 25-50%, occur during the approach and landing phases of flight (Baker, Lamb, Guohua, and Dodd, 1993; Blanchard, 1991; Hendricks, 1993). Many of these accidents may be attributed to improper instrument approach procedures. Current paper charts of instrument approach procedures (IAPs) are quite complex, containing a large amount of information in a very small area.

Glass cockpit technology now allows us to present IAPs on an electronic display. The electronic display of IAPs has a number of practical advantages which include ease of information update, format flexibility, and the ability to merge with other glass cockpit functions such as ground proximity warning systems (Mykityshyn and Hansman, 1992). EIAPs may eliminate some of the problems that are inherent in paper IAP charts through customization and decluttering techniques. However, EIAPs also may introduce new problems for pilots. For example, an EIAP may require a pilot to make display selections during the instrument approach, adding to the workload of the task. Careful consideration of potential problems must be considered early in the development of EIAPs. As part of this effort, this project reviewed the instrument approach task and the cognitive psychology literature to identify the key cognitive issues in the design of EIAPs.

1.1 Background

The first step in identifying the cognitive issues involved in the design of EIAPs was to gain a thorough understanding of the instrument approach task. This was achieved through various methods including literature review, pilot interviews, and a cognitive task analysis. A complete description of the methods and the results are provided in Appendix A--Summary of Current Practices, Operational Requirements, and Potential Cognitive Implications.

The second step in identifying the key cognitive issues was to complete a comprehensive review of the cognition literature to identify issues that are relevant to the instrument approach task. This included a review of both general cognitive psychology literature and literature specific to aviation. An introduction to cognitive psychology and related theories is also included in this report. For each cognitive issue that was identified, design guidelines and the relevance of those guidelines to the instrument approach task are provided.

1.2 Cognitive Psychology

Cognitive psychology is an extremely broad topic. Perception, learning, memory, language, reasoning, and thinking can all be included under the umbrella of cognitive psychology. A large and diverse body of research and literature related to cognitive psychology is available. The goal of human factors in cognitive psychology is to apply the body of knowledge available about how people process information to the design of systems to make them easier for humans to use efficiently and safely. The goal of this project is to apply this knowledge of human mental processes to the design of EIAP charts. Unfortunately, as human beings are very complex there is no one model of human cognition to help with this task. There are, however, a number of different theories and general principles that describe human performance under different situations that can be applied to the design of EIAP charts.

1.3 Cognitive Skills Required for the Approach Task

Prior to discussing the cognitive principles that are applicable to the design of EIAP charts, it is important to first describe the mental processes that are required for the task (for more information about the instrument approach task see Appendix A--Summary of Current Practices, Operational Requirements, and Potential Cognitive Implications). The instrument approach task is quite complex. There are a number of different cognitive skills required of the pilot. These skills include but are not limited to, the following:

- The pilot is subject to high temporal demand. Perceived workload, problem solving, and decision making performance are all highly dependent on time.

- The pilot must have a great deal of backgro nd knowledge. This includes knowledge of navigation systems and IFR rules (including a number of specific conditional rules for the instrument approach).

- The pilot must remember to perform different sequences of actions at different phases of the approach. The pilot may or may not have memory aids for each of these actions. If a pilot forgets to perform any one of a number of actions during the approach, the workload later will increase, greatly increasing the difficulty of the task.

- The pilot must be able to quickly and accurately extract needed information from various sources (ATIS, ATC, IAP chart, co-pilot, or aircraft displays) and remember the information long enough to apply it (turn to the appropriate IAP chart, enter in a frequency, set a timer, etc.).

- The pilot must be able to review and integrate the information on the approach chart to help in planning the approach and setting up expectations for the approach.

- The pilot is constantly subject to interruptions such as ATC communication which may affect memory of actions to complete and of information to apply.

- The pilot is constantly subject to requirements from ATC for changes to the planned approach.

- The actions that a pilot must perform will be highly dependent on a number of situational factors, therefore, the pilot must be able to "tailor" his or her procedures to each approach.

- The pilot's need for information is highest during the pre-approach phase. Workload is highest from the initial approach phase through landing. During the final approach, the pilot must focus on flying the aircraft and consequently the ability to contribute cognitive resources to other tasks is limited.

- The pilot must continually monitor the flight of the aircraft during the approach.

- The pilot must remain aware of the aircraft position/location throughout the approach.

- The pilot may be required to perform mental arithmetic to determine proper headings, accounting for wind.

- The pilot must use spatial abilities to rotate information on the IAP chart to match it to the aircraft's current orientation.

- The pilot uses a number of heuristics or "rules of thumb" to aid in performance of various tasks.

- The instrument approach task is a stressful situation for the pilot. Stress can reduce cognitive ability and can lead to cognitive capture or tunneling. Stress may cause the pilot to focus on one part of the task to the exclusion of other important parts of the task.

1.4 Theories

This section provides a brief summary of some of the currently popular theories in the study of cognition as it applies to tasks such as the instrument approach task. These theories are discussed so that the ideas and terms will be familiar as they are presented within the key cognitive issues for the design of EIAPs.

1.4.1 Wickens' Information Processing Model

The current model in the study of cognitive psychology as it applies to human performance views the human as an information processor. A variety of models have been developed to describe the way in which humans process information; however, there are some concepts that are consistent among the models and have proved useful in describing human performance.

A model presented by Wickens (1984) combines these concepts in a comprehensive manner. Wickens' model assumes that information is processed by humans in stages and that "each stage of processing performs some transformation on the data and demands some time for operation." Wickens' model asserts the following sequence of information processing:

1. Information is first sensed by human sensory organs (for this project, vision is most important).

2. This information is transformed into a short-term sensory store. This storage has a very large capacity but decays rapidly.

3. The information within this sensory storage that is attended to is perceived by the human. This perception is affected by the individual's long-term memory. The result of this perception is a "perceptual decision" in which the stimulus is assigned to a perceptual category.

4. Once the information is perceived and categorized, the human must decide what to do with it. Attention and resources are required for this decision, as is the use of working memory. Working memory may be used to hold the information in storage while a decision is made.

5. After a decision is made, the individual will execute a response based on that decision. Again, attention and resources are required for the execution of the response.

Wickens (1984) warns that this conceptualization should not be taken literally, that the flow of information is not fixed, and that the distinction between the stages may not be clear.

1.4.2 Attention and Multiple Resource Theory

Attention is referred to as "selectivity of processing" (Eysenck, 1984). It is the focusing or concentration on information for further processing. The importance of attention in the design of EIAPs is obvious. The instrument approach task requires the pilot to do so many different things at the same time that the ability to attend to the appropriate information at the right time is of utmost importance for the pilot's success. Wicken's describes three different types of attention--focused attention, selective attention, and divided attention--which will be discussed in detail later.

For the purposes of describing human performance, researchers have tried to develop a model that describes human attention and its limitations. Kahneman (1973) described attention as a single undifferentiated pool of resources. As a task becomes more difficult or more components are added, resources are used until there are no more resources available and further performance is degraded. However, experiments on performance of various tasks have shown that people are good at performing some tasks at the same time (time-sharing) but not very good at time-sharing other tasks. In general, the more structurally similar the two tasks that must be performed, the more difficult it is for people to perform them concurrently.

Based on these results, Wickens (1984) has proposed a Multiple Resource Theory which theorizes that humans have many different pools of resources. Two tasks will interfere more if they draw from the same pool of resources than if they draw from different pools. Wickens (1984) divides his multiple resources into stages of processing (encoding, central processing, or responding), modalities (input of information through auditory or visual means), processing codes (processing of information through verbal or spatial codes), and responses (responses can be manual or verbal). However, some studies have shown that even very different tasks will have some degree of interference when performed together, suggesting that there may be some type of "metacontroller" (Jex, 1988) or a general capacity which manages the resources for the tasks and is affected by all tasks, whether they involve competing resources or not.

1.4.3 Rasmussen's Skill-, Rule-, Knowledge-Based Model

In addition to building a model of how information is processed by humans, it is helpful to categorize different types of human information processing behavior. Rasmussen (1986) presents a model that categorizes human performance into three levels: skill-, rule-, and knowledge-based performance. According to Rasmussen, skill-based behavior takes place without conscious control as smooth, automated, highly integrated behavior. Rule-based behavior is based on a consciously controlled, stored rule or procedure that may have been empirically derived previously or communicated from others. The final level of performance occurs in unfamiliar situations when no skill or rule has been developed. In knowledge-based performance, an individual analyzes the environment and goals and develops a plan. The plan is then tested either through trial and error or conceptually through understanding the properties of the environment and predicting the effects of the plan.

Many of the concepts presented in this summary of theories will be described in greater detail throughout this report. For the purposes of this project, we will not discuss human vision or perception as it relates to the ability to detect and categorize isolated stimuli (see Mangold, Eldredge, and Lauber, 1992). We will, however, discuss perceptual categorization as it is affected by other cognitive processes such as long-term memory and attention.

2. MEMORY CONSIDERATIONS

2.1 Sensory Storage

Sensory storage of visual information, also known as iconic storage, is a very short term (less than a second) storage of nearly all of the details that are sensed by the visual system at a given time. For the design of EIAPs, it is important to know that unless information in sensory storage is attended to, it will not be processed further and will essentially be lost. Attention is discussed in detail below.

2.2 Working Memory

Working memory can be described as a "desktop" (Broadbent, 1971) that contains the information that is currently being considered. According to Wickens (1984) the information in working memory can come from three sources: 1) external stimuli, 2) mental operations, and 3) long-term memory. A large body of research dealing with short-term or working memory is available. This research is not reviewed in detail (see Ashcraft, 1988; Wickens, 1984; Klatzky, 1975); rather, two main conclusions that are pertinent to the design of EIAPs are discussed.

First, the capacity of working memory is very small; it has the ability to hold about seven chunks of information at a given time (Miller, 1956). A "chunk" can be defined as a meaningful unit of information. For example the letters "b", "t", and "a" are considered three chunks while the word "bat" can be considered one chunk of information. Therefore, if information can be "chunked" together in a meaningful form, the capacity of working memory can be greatly expanded.

Principle 1:	Reduce the amount of information that a pilot has to maintain in working memory at any given time.
Principle 2:	Display information on EIAPs so that it is meaningful, and in a manner that facilitates chunking of information that must be retained in working memory.
Relevance:	One of the cognitive tasks required of pilots during an instrument approach is to extract information from the approach plate and retain it in memory until it is applied. This information includes frequencies, altitudes, times, NAVAID names, instructions from ATC, visibilities, approach in progress, and many others.

The second conclusion based on the research of working memory is that unless resources are continuously allocated to working memory (e.g., through rehearsal), the information will decay and any operations performed on that information will deteriorate (Wickens, 1984). For information to remain current and accurate within working memory, continuous attention must be given to that information. If a person is interrupted for any reason, attention will be diverted and information in working memory will be degraded.

Principle 3:	Do not allow the EIAP to interrupt the pilot's current activities.
Principle 4:	Provide pilots with a means of quickly relocating information which may have been lost from working memory due to interruptions.
Principle 5:	If more than one display screen or mode is available, make the change of screen or mode pilot-controllable (see section on Dynamic Displays).
Relevance:	Pilots are constantly subject to interruptions during the instrument approach task, especially from ATC. It would be impossible to eliminate all interruptions during the instrument approach task, in fact, it would also be unsafe since many of the interruptions are required for safe flying of the aircraft (e.g. warnings). However, it is possible to design EIAPs that do not add to the number of interruptions a pilot has to deal with. It is also possible to provide pilots with a simple method of highlighting information so that if the pilot is interrupted, he or she can access the information again quickly.

2.3 Long-Term Memory

Klatzky (1975) describes long-term memory as a complex storehouse for our knowledge of the world. Research on long-term memory indicates that information may be encoded in a number of different ways (e.g. visually, verbally, or acoustically). There is also research to support a hypothesis that long-term memory is permanent. This would indicate that forgetting is not due to a loss or decay of information, rather it is due to a failure to retrieve information. In any case, it is known that the retrieval of information from long-term memory can be facilitated in a number of different ways.

The way in which information is encoded or transferred into long-term memory can affect an individual's ability to retrieve that information later. For example, simple rehearsal of information in short-term memory will transfer information into long-term memory. More effective recall is achieved, however, by elaborative rehearsal in which the meaning of the information is used to help store the information. While there are some experiments that refute this conclusion, it can be stated that, in general, complex, meaningful study of information in which connections and relationships are considered leads to better recall of the information (Ashcraft, 1989). Recall of information may also be related to the manner in which the information was organized in memory. This will be discussed in more detail in the section on knowledge and mental models.

The other major factor influencing the ease with which information can be retrieved from long-term memory is the presence of retrieval cues at the time of retrieval. Tulving and

Thompson's (1973) encoding specificity theory states that information encoded in memory contains not only the specific information item but also any extra information about that item that was present during the encoding. If that extra information is available at retrieval time, it will be easier to recall the information. The extra information that is encoded with the item may make a good retrieval cue (a prompt or reminder for the information to be retrieved).

Principle 6:	Display information on the display so that it matches the way the information was learned or taught, or provides retrieval cues to help prompt for the learned information.
Principle 7:	Minimize the number of coding schemes and symbols the pilot must memorize.
Relevance:	The instrument approach task requires a great deal of background knowledge of instrument navigation systems. If these systems are taught through the use of figures that demonstrate the radiation of waves from the system, then it would be possible to provide a symbol for that system that matches the figures used for training. In addition, the use of population stereotypes such as red for danger may provide context or retrieval cues for the pilot.

Long-term memory is also subject to problems due to interference (Thimbleby, 1990). This is also related to the way information is stored in memory.

Principle 8:	Avoid using symbols or codes that may conflict with a previously learned system or population stereotypes.
Relevance:	Pilots receive input from a number of different sources in the aircraft. Each of these sources has potential for conflict if the same symbol is used to mean two different things. In the design of EIAPs, care must be taken not to display information that may conflict with paper IAP charts.

2.4 Imagery and Visual Memory

Studies on memory for pictures and scenes have shown that people are very good at recognizing pictures from memory (see Klatzky, 1975 for a review).

Principle 9:	Present information that provides pilots with a mental pictorial image of what to look for.
Relevance:	Some of the information on IAP charts is provided to help pilots form a mental picture of what he or she may see during the approach. If this information is provided in pictorial form, the pilot will have good memory of what was on the chart and be able to recognize it quickly in "the real world." Huntley (1993) provided an example of this in his presentation of runway lighting information.

Paivio (1965) supports a dual-coding theory that suggests that information in memory that has both a visual and a phonetic code may be recalled more easily than information that has only a phonetic code. He showed that high imagery or concrete nouns (such as dog) were recalled easier than low imagery or abstract nouns (such as truth). Research that suggests that individuals have a mental image of information suggests also that this mental image is not precisely the same as the real image (may contain only the degree of detail that provides necessary information) and this mental image can be segmented into meaningful pieces (Anderson, 1985; Norman, 1988).

There are some problems with the memory of pictures and spatial areas. Research has shown that people are subject to some biases in the memory of visual information. People show biases toward symmetry, alignment with other figures, rotation toward a vertical-horizontal reference frame, and a tendency to cluster landmarks close together (Howard and Kirst, 1981). Fortunately these biases are most prevalent when individuals are required to reproduce visual information and the instrument approach task requires recognition of visual information.

Principle 10:	For concepts that must be recalled in the instrument approach task, provide pilots with a visual representation of the concept in addition to the name for the concept.
Principle 11:	For concepts that can be represented visually display symbols that capitalize on the mental image by making meaningful features (e.g. features that can be used to distinguish one object from another) distinctive.
Relevance:	Pilots are required to have a great deal of background knowledge of the instrument flight and navigation system for the approach task. If, during training, pilots are provided with visual representations of concepts that must be remembered, pilots will have a dual code of the information leading to easier recall. In addition, the EIAP charts could use this visual representation as a retrieval cue, making recall even easier.

3. PERCEPTION AND COGNITION

3.1 Visual Search

One of the most important issues in the design of EIAPs is the time that it takes for a pilot to search the display for needed information. Probably the most important factor which affects search speed is the degree to which items are consistently located. If an individual develops an expectation that the information will be in a certain location, search speed will be faster if the information is located there consistently. Wickens (1984) has identified a number of other factors that affect the speed at which individuals search a display:

1. The greater the similarity between features of the item to be searched and features of other items, the slower the search speed

2. The greater the number of targets that must be searched for, the slower the search speed

3. The greater the number of elements that must be searched, the slower the search speed

4. The more information on the display, the slower the search speed

5. The more practice the individual has had in the search task, the quicker the search speed

6. The number of dimensions that can be used to describe a target affects the search task--if the dimensions are non-redundant then search speed is slowed; however, if they are redundant then search speed is faster.

Principle 12:	Locate information consistently on the display.
Principle 13:	Make features of different targets as dissimilar as possible.
Principle 14:	Eliminate any irrelevant information from the EIAP display.
Principle 15:	Use redundant coding of targets (make targets different on more than one dimension--shape, size, color--see section on coding).
Relevance:	Pilots use IAP charts to quickly locate specific items of information during the approach task. Minimizing the time required for this task is of great importance in the design of EIAPs. Pilots are under a great deal of time pressure throughout the approach. It is possible to locate some search targets on the approach plates consistently from chart to chart (e.g., ATIS frequency, minimum visibility). Some items may be located both spatially (in terms of a world reference frame) and consistently (as is done in Huntley's "briefing strip"). For those items which can not be located consistently, the recommendations to make them distinctive and use redundant coding are especially important.

3.2 Pattern Recognition

Neisser (1976) defines pattern recognition as "The process of assigning objects or stimuli to categories . . ." Theories of pattern recognition include template theories, prototype theories, and feature detection theories. Each of these theories has shortcomings and template theories are usually dismissed completely. An argument between the validity of prototype vs. feature detection theories leads to a discussion of top-down (concept-driven) vs. bottom-up (data-driven) processing. Perception of information is a combination of two types of processing--top-down processing is an analysis of the holistic properties of the stimulus, utilizing context and expectations; bottom-up processing is a detailed analysis of stimulus information. When viewing conditions are poor, people are required to rely more on top-down processing (Eysenck, 1984). There are two important ideas that come out of these theories and research on pattern recognition:

1. The more clearly the features of the pattern are presented, the more easily the object is recognized (helps bottom-up processing).

2. The more information that is provided by context (sets up expectations), the more easily the object is recognized (helps top-down processing).

Related principles:	2, 6, 13, 15
Principle 16:	Make object features distinctive. This can be done by increasing the size of the object, using redundant coding such as size and color (Principle 13), or by making the shape of the object distinct from the shape of other objects (Principle 11).
Principle 17:	Provide context for items that must be identified quickly. Context can be provided by using shapes which are meaningful (Principle 2), by providing retrieval cues (Principle 6), by displaying related items or information. In the case of verbal material, context could be provided for a word by displaying it within a meaningful sentence.
Relevance:	The speed and ease with which a pattern is recognized and appropriately categorized is extremely important to an IAP Chart user. The design of displays which provide the most clear "features" and relevant context will help with this recognition.

3.3 Mental Rotation

Another factor that affects the speed of recognizing a pattern is the amount of transformation or rotation that must be performed on the image. Researchers have shown that when people are asked to determine whether an image matches one they have seen previously, the time that it takes increases with the amount of transformation of the image from the original (Anderson, 1985).

Principle 18:	If a moving map is used, display symbols with an upright orientation at all times (horizontal text).
Relevance:	The instrument approach task requires pilots to be able to quickly recognize information on the approach plate. Symbols with a consistent orientation will facilitate speed of recognition. Pilots also are required to match the image of the outside world to the image of the approach plate. A static EIAP does not allow the pilot to physically rotate the image as can be done with a paper chart. Unfortunately a dynamic EIAP that maintains a track-up orientation (and does not require mental rotation) presents a number of other problems which are discussed in detail in the section on dynamic displays.

3.4 Display Clutter

Clutter is the problem most frequently encountered in the current design of IAP charts. Unfortunately, clutter is a difficult concept to define and is even more difficult to quantify. An individual perceives display clutter when relevant information is difficult to locate and identify on a display due to the existence of irrelevant information on the display. Display clutter is a problem any time a large amount of information must be displayed in a small amount of space. There are a number of factors that affect the perception of clutter on a given display:

1. The density of information on the display

2. The perceptual discriminability of information on the display (two symbols would be less perceptually discriminable than one symbol and one line of text)

3. The discriminability of the meaning of different information elements on the display (the final approach fix indicated by a symbol and the decision height indicated by an altitude (in text) may be less discriminable in terms of meaning than the final approach fix symbol and an obstacle symbol)

4. The user's familiarity with the information on the display (both relevant and irrelevant information)

5. The user's familiarity with the grouping and organization of information on the display

The last three factors in this list indicate that the implicit knowledge that a user brings to the task has an effect on perception of display clutter. A display that appears cluttered to a novice user may not appear so to an experienced user.

Related Principles:	5, 12, 14. See sections on mental models (5.1), organization and grouping of information (7), and direct perception and integration of information (8).
Principle 19:	Eliminate any irrelevant information from the EIAP display (Principle 12). This includes removal of information such as minimums for other aircraft types or military aircraft.
Principle 20:	Display text and symbols that are visually distinct (Principle 14).
Principle 21:	Increase the discriminability of the display through the judicious use of coding and highlighting (see section on coding).
Principle 22:	Increase the discriminability of the display through use of blank space and organization of information on the display (see section on organization).
Principle 23:	Display information in its most integrated form (see section on direct perception and integration).
Principle 24:	Group and organize information in a meaningful manner (see section on grouping and organization).
Relevance:	EIAPs present the approach plate designer with possibilities for the reduction of display clutter that were not available to paper chart designers. Specific information about the aircraft and the route could be provided pre-flight to the EIAP so that the displayed plate can be customized, with much more of the irrelevant information removed. This, of course, will reduce search time for the relevant information. EIAPs also afford the possibility of presenting information on separate screens or in "layers." However, the method of switching screens will have to be carefully evaluated. To facilitate the extraction of meaning of elements on the display screen, it is necessary to understand how the pilot views the relationships between information elements on the display (see section on mental models).

Schultz, Nichols, and Curran (1985) researched decluttering of a graphic display by removing or minimizing information of lesser importance. They found that removing text and making less important symbols smaller was as effective a decluttering technique (in terms of search time for the important items) as was complete removal of the less important items. Schultz et al (1985) concluded that ". . . the effectiveness of decluttering methods depends upon the degree to which each method makes essential graphic information distinctive from nonessential information."

Principle 25:	Make information which is currently necessary distinct from information which is displayed but may not be essential at that time.
Principle 26:	After all other options have been considered, if clutter is still a problem--increase the size of the display or display the information on separate screens, grouped in a meaningful manner (see Principle 5 and later sections on organization and grouping).
Relevance:	This selective declutter has interesting implications for the approach task since there may be reasons to show symbols for NAVAIDs which the pilot does not plan to use (yet may nonetheless want to know what options are available), but it may not be necessary to display all of the information associated with them unless it is specifically requested. Decluttering of essential information is possible without complete removal of non-essential information, which may be requested if needed. Thus, another method of "layering" information without complete removal of information is provided.

4. ATTENTION AND PERFORMANCE LIMITATIONS

4.1 Focused Attention

Focused attention refers to an individual's ability to concentrate on one important source of information (Wickens, 1984). The individual must be able to locate a critical item of information quickly while shutting out other unwanted stimuli that may capture attention. A pilot must use focused attention to extract one frequency from an approach plate. Focused attention can be facilitated by stimuli that draw attention to themselves. Stimuli that conflict with expectations, are novel or surprising may draw attention to themselves. Most of the methods that facilitate focused attention also reduce visual search time and reduce display clutter and have already been discussed.

Related Principles:	3, 12, 13, 14, 16, 19, 20, 21, 22, 23, 24
Relevance:	The facilitation of focused attention will help the pilots to extract needed information quickly and accurately. However, care must be taken to ensure that methods used do not interfere with a pilot's ability to direct or divide attention properly (see Selective and Divided Attention below).

4.2 Selective Attention

Selective attention refers to an individual's ability to select the appropriate information from a number of different sources. Pilots' sampling of information from various sources (scan patterns) is an example of the use of selective processing. People are limited in their ability to sample appropriate information and will sample inappropriate information instead if it is more salient. Problems with selective attention may be related to display clutter. Individuals also may become preoccupied with certain events and may not select the information that needs to be sampled at a given time. This is often referred to as cognitive tunneling. Wickens (1984) summarizes four conclusions based on research on selective attention:

1. Sampling is guided by the individual's model of the statistical properties of the environment.

2. People learn to sample more frequently those displays which indicate higher event rates.

3. Memory lapses and imperfections lead to more frequent sampling than is optimum.

4. A preview of future events helps to optimize sampling and switching.

Related Principles:	25, 26
Principle 27:	Locate frequently sampled information centrally.
Principle 28:	Information items that are often sampled sequentially should be located close together.
Principle 29:	Design the display to facilitate the preview of future events.
Principle 30:	Avoid presenting information in such a way that inappropriate information is more salient than appropriate information. Motion, color, highlighting, and size may make information more salient. These features may also induce cognitive tunneling so that attention remains focused on inappropriate information.
Relevance:	The EIAP is required to present a large amount of information and the pilot must be able to select the appropriate information on the display at the appropriate time. Unless the exact situation is known, it is impossible to predict what information is needed for the pilot. However, it is possible to help the pilot by following these principles. It has already been stated that the pilot uses the display for two purposes--first for planning, then for extracting specific information. A planning display should allow the pilot to preview and select information needed for future events so that he or she will be able to quickly extract the appropriate information when it is needed.

4.3 Divided Attention

Divided attention is the ability to divide attention between two or more stimuli or tasks. Attention is not strictly serial. A channel model in which a channel is defined as a spatial area (one degree of visual angle), a common pitch, or the grouping of related meanings (Wickens, 1984) is often used in the discussion of divided attention. Attention can be focused on one channel so that information within one channel can be processed in parallel. This parallel processing can be either harmful or helpful. Parallel processing is helpful if two tasks have independent implications for action or if both sources of information imply the same action (an example is the use of redundant codes). Parallel processing may be harmful if resource competition occurs or if the action performed on unwanted information within the channel competes with action performed on wanted information within the same channel.

Related Principles:	See sections on display clutter (3.4), multiple resource theory and resource competition (4.6), and coding (9).
Principle 31:	If two items or tasks should be processed in parallel, locate them spatially within one channel.
Principle 32:	If two items require two different actions which may be competing, separate them spatially.
Principle 33:	Never use two codes for one symbol that have different implications for action or different meanings. For example do not use the shape of a stop sign with the color green.
Relevance:	The instrument approach task requires pilots to be very good at dividing attention. There are many situations where a pilot can and does process two different bits of information at the same time. For example, a pilot may identify the appropriate NAVAID name while at the same time remembering the frequency for that NAVAID on the EIAP. A problem arises when the two different sources of information imply different implications for action. For example, if red indicates a NAVAID frequency and a box around the numbers indicates a radio frequency, red numbers with a box around them would cause problems for the pilot.

4.4 Workload Effects

Workload is a concept that has received a great deal of attention in human performance literature. Gopher and Donchin (1986) state that "workload is invoked to account for those aspects of the interaction between a person and a task that cause task demands to exceed the person's capacity to deliver." Changes in the difficulty of the task or tasks and the operators' interpretation of that difficulty can be described by the workload of the task. In the case of EIAP display design, workload is important in that it is often related to operator performance.

Moray (1982) presents a list of factors that affect perceived difficulty:

- the requirement to generate lead (predict)
- physical effort
- number of alternative solutions
- quality of data
- uncertainty about the consequences of action
- conflicting demands with respect to desired outcomes
- need for feedback
- scarcity of time (time pressure)
- expenditure of energy
- probability of failure
- motivation

The following factors may also be added to the list:

- the number of tasks that must be performed
- the number of tasks that must be performed concurrently
- the number of items that must be maintained in memory
- the psychological stress of the tasks

In general, any time more tasks, competing tasks, or more complex tasks are required, workload is increased and may lead to a breakdown in performance. An exception occurs when task difficulty is so low that the task is boring--an increase in workload may actually lead to better performance. Many of the factors listed above are discussed in detail in the following sections.

Related Principles:	1, 2, 3, 4, 6, 7, 25, 26
Principle 34:	Whenever possible, predict future states automatically.
Principle 35:	If relevant, reduce the amount of time that must be spent controlling (setting, selecting) the EIAP and searching for information on EIAP (see section on Visual Search).
Principle 36:	Make clear the consequences of any action on the EIAP before the action is taken.
Principle 37:	Reduce the number of tasks that must be performed--don't add any new tasks in the design of an EIAP.
Relevance:	Based on the above factors affecting workload, it is obvious that the instrument approach can be considered a high workload task. Pilots are required to generate lead ("fly ahead of the aircraft"), consider a number of alternatives, perform a number of different tasks (some of them concurrently), and experience very high time stress.

4.5 Depth of Processing: Controlled vs. Automatic

Rasmussen's model suggests that higher levels of processing cause a task to have a higher level of workload. In fact, Reason (1990) states that ". . . human beings are strongly biased to search for and find a prepackaged solution at the RB [rule-based] level before resorting to the far more effortful KB [knowledge-based] level, even where the latter is demanded at the outset." Vicente and Rasmussen (1992) use this knowledge in their framework called ecological interface design (EID). In EID, the goal is not to force processing to a higher level than the demands of the task require.

Related to Rasmussen's model is Schneider and Shiffrin's (1977) classic distinction between automatic and controlled processing. "A controlled process is one that requires attention and takes up capacity; an automatic process is a well-learned behavioral sequence that is automatically triggered by some cue or signal and that does not require attention or compete with other processes for capacity (such as memory capacity)" (Chase, 1986). Automatic processes can operate in parallel with other processes. Within the framework of Rasmussen's model, automatic processes can be equated to skill-based processes. Within the framework of multiple resource theory, automatic processes operate without consuming any resources (although there still may be structural interference).

Logan (1988) questions the distinction between automatic and controlled processing, hypothesizing that there is not a distinct difference between the two, rather automaticity occurs along a continuum with a task becoming more and more automated with increased practice. Theoretical arguments aside, it is true that continued practice of tasks which require consistent responses to consistent stimuli do promote fast, effortless performance that does not consume attentional resources. There are, however, some problems with this type of process since it is sometimes difficult to stop an automatic process once it has started. This problem is discussed in more detail in the section on human error.

Related Principle:	12
Principle 38:	Use symbols consistently within the EIAP and between other cockpit displays to promote automatic or skill-based processing.
Principle 39:	Display information in a manner that promotes rule-based processing as opposed to knowledge-based processing (see sections on Problem Solving and Reasoning, and Direct Perception and Integration of Information)
Relevance:	During an instrument approach, the pilot is required to divide his or her attention between a number of different tasks. If extracting information from the EIAP can be automated, it will occur more quickly and interfere less with the pilot's other tasks. Also, when the pilot must process information on the EIAP at a higher level, it will be done more quickly and with less effort if it can be done at a rule-based level rather than a knowledge-based level. The sections on Problem Solving and Reasoning, and Direct Perception and Integration of Information provide more insight into how rule-based processing can be promoted.

4.6 Time-Sharing and Resource Competition

Task workload also is affected by the degree of resource competition for that task. Multiple resource theory (Wickens, 1984) predicts that if two tasks demand separate resources, time-sharing will be more efficient and changes in the difficulty of one task will be less likely to influence performance on the other task than if two tasks demand common resources. For example two tasks which require a visual input and a manual output will interfere more (resource competition) than a task which has a visual input and a manual output and a task which has an auditory input and a verbal output. There is also some evidence for a compatibility effect for central processing codes. Tasks which require verbal working memory may best be served by auditory inputs while tasks which require spatial processing are best served by visual inputs.

Principle 40:	Take advantage of multiple resources by displaying both verbal and spatial information.
Relevance:	Tasks performed by pilots during an instrument approach require that the pilot use a number of different resources. The pilot is receiving both visual and auditory input, using both spatial and verbal processing, and making both verbal and manual responses to the information. Unfortunately, the EIAP is limited to providing visual information and the information, in general, initiates a manual response. This leaves only manipulation of the display of verbal or spatial information as a way to help reduce resource competition. It also is difficult to specify what other tasks a pilot will be performing (he may be using spatial skills to fly the aircraft and/or verbal skills to listen to and respond to ATC) while he is using specific items of information from the EIAP. In fact, it is probably better to determine whether presentation of information should be spatial or verbal based on the nature of the task (e.g., information that requires spatial processing should be presented spatially) than to make any attempt to display it so that it does not compete with other tasks in the cockpit. However, the general recommendation that the information presented should be a mixture of both verbal and spatial information may help eliminate some resource competition. In addition, testing of the EIAP should include examination of the use of the EIAP within the entire task for potential resource competition.

4.7 Stress Effects

Many of the factors listed by Moray (1982) as affecting workload are stressors. Stress (caused by uncertainty, time pressure, etc.) affects a person's ability to perform. Researchers have shown that individuals under stress have a reduction in working memory capacity, sample information with non-optimal strategies (they may pay attention to only one source of information--a phenomenon known as cognitive tunneling), and may continue attempting an unsuccessful solution (often termed perseveration). Stressors significantly affect the early stage of decision making by disrupting scan patterns, adversely influencing which elements are attended to, and reducing the number of elements attended to (Endsley and Bolstad, 1993). In contrast, Wright (1974), found that, under time stress, decision-making performance deteriorated when more information was provided. People sought more information than they could effectively absorb. In either case, stress affects performance, especially the ability to focus attention on the appropriate information.

Related Principles:	1, 2, 3, 4, 6, 7, 12, 13, 14, 15, 21, 22, 24
Principle 41:	Under high stress situations, display important information so that it is highly salient.
Relevance:	The instrument approach is one of the most stressful situations for a pilot. Bad weather and time stress affect a pilot's ability to perform. A missed approach is a good example of a stressful situation for a pilot. The pilot must get up and out of the airport area quickly and is uncertain of the next actions to take. It is at this time that an EIAP should automatically, by pilot selection, highlight only the information that is pertinent to the missed approach (i.e., missed approach instructions and terrain in the missed approach area).

4.8 Errors (Skill-Based)

There are a number of errors that are common in humans when performing tasks at a skill-based (or automatic) level. A summary of the error types discussed by Reason (1990) is presented below:

- **Double-Capture Slips**: This type of error is due to the failure of attention at some time during a skill-based activity. At the time that the person fails to attend (or omits a check in the sequence), the strongest or most highly automated, related sequence of actions takes over. For example, a person wants to make a change to his or her daily routine (e.g. stop at the store on the way home) but continues on with the routine without making the change (drive right by the store without stopping).

- **Omissions Following Interruptions**: The second type of error due to inattention occurs when the performance of some skill-based sequence of actions is interrupted. After the interruption, the sequence is continued but the steps that should have been taken immediately following the interruption are omitted. For example, a pilot plans to set the NAV1 receiver to the primary NAVAID and the NAV2 receiver to the secondary NAVAID. The pilot reads the primary NAVAID frequency and starts to set the NAV1 receiver but is interrupted by ATC. After responding to ATC the pilot returns to the task, setting the NAV2 receiver without completing the setting of the NAV1 receiver.

- **Reduced Intentionality**: This type of error occurs when an individual sets out intending to perform some act but his or her attention is captured by something else in the environment. After responding to this the person no longer remembers what the original intention was. This is the familiar "why am I here" error.

- **Perceptual Confusions**: This type of error occurs when people accept as a proper object for the job something that looks like the object, is in the expected location, or performs a similar function (e.g. putting the cereal box in the refrigerator).

- **Interference Errors**: These are errors in which two different automated tasks with some similarities are confused or mixed (e.g. answering the telephone at home with "Monterey Technologies, may I help you?").

- **Omissions**: In addition to errors of inattention, there are also errors of overattention or mistimed checks. Omissions occur when one checks a sequence and concludes that it has completed before it actually has (similar to omissions due to interruptions).

- **Repetitions**: Repetitions due to overattention occur when one checks a step in an automated process and determines that a step that has already been performed has not, and performs the step again.

- **Reversals**: This type of overattention occurs when a person prepares to perform some action (getting money out to pay at the grocery store), then, before completing the action, reverses it (puts the money away before the cashier has collected it).

Thimbleby (1990) adds to this list "termination error" which is an error that occurs when some act leads a person to "closure" before the entire act is completed (e.g. leaving your card in a money machine after you have received your money).

Related Principles:	1, 3, 4, 7, 8, 12, 13, 15, 24, 38
Principle 42:	Provide a means of keeping the pilot aware of where he or she is in a sequence of activities.
Principle 43:	Provide the pilot with a method to annotate any unusual activities for a given approach.
Principle 44:	Provide reminders of any crucial steps in an approach sequence.
Principle 45:	If consistency of location of an information item is used to promote skill-based processing--it must **always** be followed.
Relevance:	Many of the actions that a pilot must take during an instrument approach are well-learned, skill-based sequences subject to many of the above errors. Errors of this sort during an approach can be very dangerous if they go unnoticed. Many of the principles already mentioned--consistency of location, consistency of symbol use, distinctiveness of symbols--will reduce this type of error. In addition, current checks such as checklists are already used by pilots to remind them of crucial steps. It is important that no additional activity by the pilot be required for the implementation of principles 37 and 38.

5. KNOWLEDGE

Cognitive psychologists often divide the representation of knowledge into two types of memory--episodic memory and semantic memory. Episodic memory is autobiographical memory of events. Semantic memory refers to the memory of concepts and their relationships. Semantic memory is highly organized to allow for fast retrieval of information. The line between episodic and semantic memory is hazy since much of the information in semantic memory is transferred through episodic memory (Tulving, 1972 in Eysenck, 1984). A model of the way information is represented or organized in memory may provide some insight into the way an individual thinks about and performs a given task.

5.1 Mental Models

Models of the representation and organization of information in the mind are often called mental models. Norman (1988) states that mental models are "the models people have of themselves, others, the environment, and the things with which they interact." A mental model is developed based on experience, training, perceived actions, and visible structure (Norman, 1988). Mental models are dynamic (Rouse and Morris, 1986). According to Cannon-Bowers, Tannenbaum, Salas, and Converse (1991), mental models serve a heuristic function. A model speeds the rate of comprehension by allowing situations, objects, functions, and relationships to be classified by important or salient features. Cognitive task analysis techniques try to determine the structure and content of mental models (see Appendix A for an initial cognitive task analysis of the instrument approach task).

Of course, each individual's mental model of a particular system may differ from those of others. Novices tend to have mental models that rely on surface features while experts have models that are organized by deeper underlying principles (Chi, Feltovich, and Glaser, 1981). Cannon-Bowers et al. (1991) suggest that training of an explicit conceptual model will direct and focus trainees on important components and relationships, will help trainees to organize information, and will help trainees to integrate the information with existing knowledge. In addition, such training will minimize differences between individuals' mental models and may lead to more complete and accurate mental models. Cannon-Bowers et al. (1991) caution, however, that training conceptual models may not be valuable if the models are very simple, very complex, or do not support inferences which are necessary for operation of the system.

Much of the literature on the design of human-computer interfaces suggests that many of the errors that are made are a result of discrepancies between the designers' model of the system and the user's mental model of the system. This suggests that, as an alternative to training a conceptual model, it may be beneficial to determine the structure and content of the user's mental model and design the system interface to match the user's existing model.

Related Principles:	6, 8, 9, 25, 26
Principle 46:	Provide pilots with a conceptual model of the functions of the EIAP system.
Principle 47:	Make functions of the EIAP visible to the user.
Principle 48:	Design the EIAP to be consistent with pilots' mental model of the instrument approach task.
Relevance:	Research on mental models may be applicable to this project in two different ways. First, pilots will form a mental model of the new EIAP. The EIAP should be designed so that all functions are directly visible, enabling pilots to form an accurate mental model of how the system works. A conceptual model (a graphical representation of the EIAP system) should be provided for training purposes on the new EIAP system. Second, pilots already have a mental model of the instrument approach task and related systems. The EIAP should be designed to support this existing model.

5.2 Implicit vs. Explicit

The distinction between implicit knowledge and explicit knowledge is important for the design of displays. Implicit knowledge refers to the knowledge that an individual brings to the task. Norman (1988) refers to implicit knowledge as "knowledge in the head." Explicit knowledge is knowledge that is obtained during the task or "knowledge in the world." Implicit knowledge is information that is obtained from long-term memory while explicit knowledge is obtained from sources directly related to the task at hand.

There are advantages and disadvantages of both types of knowledge. Explicit knowledge acts as its own reminder. It is easier to learn, but more difficult to use. Implicit knowledge is very efficient. It does not require search and interpretation of the environment as does explicit knowledge. However, implicit knowledge requires some event or stimulus to act as a reminder so that the knowledge is retrieved (Norman, 1988).

Related Principles:	6, 7, 8, 9, 42, 44, 46, 47, 4-
Principle 49:	Determine and provide the appropriate level of knowledge in the world to promote a good conceptual model of the system on the part of its users: this requires consistency of mapping between the designer's model, the system model and the user's model (Norman, 1988).
Relevance:	The basic purpose of the EIAP is to provide the pilot with the explicit knowledge needed for the task. It is important to make the appropriate determination of what information should be presented explicitly and to display the information in a manner that matches the pilot's implicit knowledge of the task.

5.3 Situation Awareness

Situation awareness is defined by Endsley (1987) as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future." It is used by pilots to refer to their awareness of the state of their aircraft, the environment surrounding the aircraft, and their ability to predict future states ("fly ahead of the aircraft"). It refers to the pilot's ability to sample and remain aware of all the pertinent information available. Researchers have applied many of the concepts from the literature of research on cognition to suggest means of improving situation awareness. The literature available on situation awareness reiterates principles already discussed related to short-term memory, long-term memory, attention, stress, workload, clutter, filtering of information, and integration of information (Endsley and Bolstad, 1993).

5.4 Mental Maps and Navigation

Thorndyke (1980) proposes that knowledge of geography changes qualitatively through a progression of three levels. First, individuals attain "landmark knowledge" of an area. They describe or navigate through an area via references to landmarks. Second, route knowledge, knowledge of the route with an ego-centered reference frame, is attained. Finally, survey knowledge, or knowledge of the area with a world reference frame, is achieved. Route knowledge shares properties with track-up or inside-out displays while survey knowledge can be compared to north-up or outside-in displays. Wickens (1984) states that ". . . possession of route knowledge is optimal for judgements made from one's own frame of reference . . . In contrast, individuals possessing survey knowledge should be relatively poor at these tasks but better at tasks requiring an independent, world frame of reference." Route knowledge will be obtained from dir ct navigation while survey knowledge will be directly obtained through studying maps and eventually through navigation (Thorndyke and Hayes-Roth, 1978).

Further research reviewed in Wickens (1984), suggests that route lists may be better for navigation tasks while maps are better for planning purposes. The problem with using only a route list for navigation is that if one becomes lost, the information on the list becomes meaningless.

Knowledge of the geography of an area may be encoded spatially in memory. "Mental map" or "cognitive map" are the terms used to describe this spatial representation in memory. The biases that humans are subject to in visual memory (see section on visual memory) can also be applied to mental maps. In addition, people have a tendency to cognitively distort the world toward a North-South-East-West orientation and will describe the location of cities by reliance on the "higher order" information of the location of states or countries (see Wickens, 1984 for a review).

Related Principles:	49
Principle 50:	Provide a spatial map when the display is to be used for planning purposes.
Principle 51:	Provide route instructions in addition to the spatial map when the display is used for navigation purposes.
Principle 52:	Show the locations of prominent landmarks on the spatial map.
Relevance:	Pilots use approach plates for two purposes--planning and navigating the route. Providing pilots with a spatial representation of information will facilitate planning. During navigation the pilot is more interested in retrieving specific information quickly. If the pilot is able to specify the route during the planning stage, the EIAP can provide the necessary information for navigation in a sequential display (similar to a route list). The implications of changes in plan must be carefully considered prior to implementing this type of function. Providing the pilot with prominent landmarks on the EIAP will help in navigation through unfamiliar areas.

6. PROBLEM SOLVING AND REASONING

6.1 Reasoning

Research in the area of problem solving and reasoning may provide some insight into the way people think about and solve problems and make decisions. It has already been stated that people prefer to use pre-packaged rule-based solutions rather than apply knowledge and reasoning to solve a problem. In fact, people are so strongly inclined to solve problems and make decisions in this manner that they will continue to use a pre-packaged solution even if it takes more time and is less effective than an independently reasoned solution (Luchins, 1942). This tendency is often referred to as a negative set (Ashcraft, 1988) or perseveration. This is also related to a tendency toward functional fixedness in which individuals will only use an object or concept in a problem environment in its customary and usual way even if an alternative use of that object will solve the present problem (Ashcraft, 1988).

In general, the research available in this area leads to two important concepts that may have application to EIAP display design: 1) the use of heuristics (rules of thumb) to make decisions and solve problems and 2) the biases that these heuristics may introduce (both heuristics and biases are discussed further in this section). Ashcraft (1988) offers the following recommendations to facilitate problem-solving:

- Increase domain knowledge
- Automate components of the task (see section on Depth of Processing)
- Formulate a systematic plan
- Draw inferences
- Develop subgoals
- Work backward
- Search for contradictions
- Search for relations
- Reformulate the representation of the problem
- Represent the problem physically
- Practice

Following these recommendations will help the problem-solver to find an accurate solution to the problem and may reduce the likelihood that biases will negatively influence the result.

Related Principles:	12, 25, 38, 39, 48. See also sections on organizing and grouping of information (7) and direct perception and integration of information (8).
Principle 53:	Design the EIAP to facilitate the planning of the approach (see section on Planning)
Principle 54:	Make relationships between information visible and clear.
Relevance:	Most of the reasoning in the instrument approach task takes place during the planning stage. Some of the tasks during the approach, such as determining headings to stay on a localizer course, may require reasoning by novice pilots, but generally heuristics (rules of thumb) are learned and automated for these tasks. The EIAP should be designed to facilitate the pilot's task of planning the approach. Relationships between pieces of information should be visible and clear and should be presented in a manner that matches the pilot's expectations.

6.2 Decision Making

Much of the research on reasoning deals with the manner in which people make decisions. The difficulty of a decision task is determined by the number of inputs to the decision, the possible outcomes of a decision, and the number of mental multiplications or summations that may be required to get a weighing of the possible options. Humans have a limited ability to consider more than three or four hypothesis at once. This leads to an initial elimination of potential correct decisions (Wickens, 1984). Stress (including time stress) also affects the way in which decisions are made (see above section on stress). The same heuristics and biases that affect a person's reasoning skill affect a decision-making task.

Decision-making aids automatically reduce the amount of information presented to what is most important for making the decision. A computer may be used to integrate information. Training to make individuals aware of potential biases, more comprehensive and immediate feedback, and the emphasis of "real" causal relations may also help a person to make the best decision (Wickens, 1984).

Related Principles:	1, 2, 25, 26, 48. See also section on direct perception and integration of information (8).
Relevance:	Pilots must make decisions continually throughout the descent, from decisions about which heading to take to decisions about speed, altitude, and control settings. Principles related to these decision making abilities are discussed at more specific levels in the following sections on heuristics, biases, errors, effects of interruptions, planning, and mental arithmetic.

6.3 Heuristics

Heuristics are previously-learned rule-based sequences that people apply to problems. Heuristics may be learned through experience or they may be specifically taught. Certainly pilots are taught heuristics (such as "double the error" to turn the aircraft back on a localizer course). Heuristics simplify the complexity of decision making and reduce the demands on attention and working memory. Some of the more general heuristics that people use are discussed below (Tversky and Kahneman, 1982, Wickens, 1984).

- **Availability Heuristic**: People make judgements about the frequency or likelihood of an event based on the ease with which instances or occurrences can be brought to mind. For example, a pilot may guess at the likelihood that ATC will provide a vector to a certain fix based on how easily he or she can recall similar situations.

- **Representativeness Heuristic**: People will judge the likelihood of some action or event generating another event by the degree to which one resembles the other. For example, a pilot may judge the ability of an Air Traffic Controller by the degree to which his or her voice is steady and calm.

- **Adjustment and Anchoring Heuristic**: Estimates that people make are more strongly influenced by early than late information. For example, if a pilot must estimate his or her average speed, the estimate is likely to be anchored closer to the speed of the plane at the time of the estimate than its landing speed.

In general, the heuristics that people use to make judgements and solve problems are beneficial. It may actually be true that an Air Traffic Controller whose voice is steady and calm is more experienced (and possibly more reliable) than the Air Traffic Controller whose voice sounds shaky. However, the relevance of the information provided by use of heuristics lies in the biases that they induce and, in the case of heuristics specific to the instrument approach task, the errors they may cause.

Related Principles:	See sections on biases (6.4) and rule-based errors (6.5).
Relevance:	Pilots utilize a number of heuristics to help them determine times, distances, corrections, etc. quickly and with little mental effort during the instrument approach task. Improper use of these rules may lead to errors. Pilots are also subject to the heuristics discussed above while attempting to solve problems and make decisions.

6.4 Biases

The tendency of people to use heuristics to reduce attentional and working memory demands leads to a number of biases (Kahneman, Slovic, and Tversky, 1982; Wickens, 1984; Thimbleby, 1990):

1. People tend to overestimate the strength of cause-effect relationships. They tend to assign cause and effect relationships when none exist.

2. People perceive the occurrence of rare events as more frequent than is true. This often leads to more conservative decisions.

3. Since humans use an availability heuristic, they are often influenced more strongly by salient or recent information rather than valid information.

4. An undue amount of weight is given to early information.

5. After people create hypotheses based on early information, they seek out information to confirm it. This is often called the confirmation bias. People have trouble dealing with negative information and often find it difficult to change an initial hypothesis.

6. As the number of sources of information increases beyond two, people are unlikely to use it.

7. There is a tendency to treat all information as if it were reliable even when the source of the information is questionable.

8. People tend to be overconfident in their judgements. This overconfidence increases with experience and can add to the difficulty people have in changing hypotheses, with the result that they create even greater problems.

Related Principles:	1, 2, 6, 7, 8, 15, 17, 19, 21, 22, 24, 25, 26, 36, 41, 48, 49.
Principle 55:	If possible, provide the pilot with an option to have important information highlighted when the situation warrants it (for example, highlight terrain information if the altitude of the aircraft drops below certain criteria--once the pilot has noted the information, he or she could deselect the highlight.)
Relevance:	Many of the principles already discussed deal with methods of making important information salient and easy to attend to and recognize. This will help pilots to overcome any biases they may have. One other way of helping pilots to overcome biases is to force them to verify information sources, hypotheses, and decisions. Many of these checks already exist for pilots (requirements to read back information, checklists, etc.) Another forced checklist on a computer would probably be too time consuming and would add unwanted difficulties to the task. However, it may be possible for the computer to automatically check pilots' choices and decisions (potentially by noting choices of information to view and planning choices), and if a potential for error exists, to alert the pilot to view appropriate information. Of course any radical automatic changes should be tested for effects on the pilot's ability to attend to other information.

6.5 Errors--Rule-Based and Knowledge-Based

In addition to skill-based errors previously discussed, Reason (1984) classifies and describes both rule- and knowledge-based errors. "In any given situation, a number of rules may compete for the right to represent the current state of the world." For a rule to compete it should 1) match the situation, 2) have been successful in the past, 3) be fairly specific to the situation, and 4) have support from other rules. Errors occur when a good rule is misapplied to a situation or when a bad rule is applied. Misapplication of good rules often occurs when the situation in which they are applied is changed slightly from previously acceptable situations. General rules are often stronger than specific rules since they are successful more often. People tend to be rigid with rules, if it was successful in the past, they will continue to use it, even if it is non-optimal (Reason, 1984).

A bad rule is created when properties of the problem space are encoded inaccurately or not encoded at all. If you use the rule, "i before e except after c" in spelling the word "weigh" you would be incorrect. The more specific property of the rule "or when it sounds like a, as in neighbor and weigh," may not be encoded at all. Rules may be wrong, or they may be just inelegant, clumsy, or inadvisable. For example, in some situations people may learn error recovery rules rather than error avoidance rules (Reason, 1984) (the driver who successfully avoids many near misses is not as good as the driver who never experiences near misses).

Failure at the knowledge-based level is more dependent on the reliance on heuristics and associated biases. Whether attention is directed to the logically important rather than the psychologically salient aspects of the problem determines the success of reasoning.
One other common error type that should be noted is "Failures of prospective memory--forgetting to remember to carry out intended actions at the appointed time and place--are among the most common forms of human fallibility (Reason & Mycielska, 1982)."

Related Principles:	1, 2, 6, 7, 25, 26, 36, 41, 43, 46, 47, 48, 54. See also section on direct perception and integration of information (8).
Principle 56:	Exploit the power of constraints, both natural and artificial. Constraints guide the user to the next appropriate action of decision (Norman, 1988).
Principle 57:	Design for errors. Assume their occurrence. Plan for error recovery. Make it easy to reverse operations and hard to carry on non-reversible ones. Exploit forcing functions (Norman, 1988).
Relevance:	Rule-based errors must be considered both in their application to the instrument approach task and their application to use of the EIAP. If the EIAP presents information in a form such that the pilot does not have to perform mental manipulation on it to use, then the possibility for rule-based errors is reduced. If the information on the EIAP is presented in a manner that matches the pilots conceptual model of the system, both rule- and knowledge-based errors are minimized. The design of any controls or selection capability of the EIAP should use constraints to prevent people from making errors and provide for easy error recovery where errors may be possible.

6.6 Effects of Interruptions

Many of the effects of interruptions have been mentioned throughout this report. However, the potential for interruptions during the instrument approach task is so great that a summary of the effects of interruptions is warranted. For each of the following descriptions, refer to the appropriate section in the report for more information:

- **Attentional Effects:** Interruptions cause a diversion of attention. This can affect a person's ability to focus attention and to divide attention properly.

- **Working Memory Effects:** When attention is diverted, it is taken away from working memory. Often the information in working memory is lost. If the pilot was remembering a frequency, he or she will have to find it again.

- **Search Time Effects:** Obviously, if a person is interrupted and has to seek information again, search time will be affected. In addition, if a person is interrupted during a search for information, he or she may have to begin the search again, increasing overall search time.

- **Skill-Based Errors**: Many of the skill-based errors are initiated by interruptions. Of course "omissions following interruptions" are due to interruptions, but many of the other skill-based errors may also be initiated due to a lack of attention.

- **Reasoning and Planning Effects**: The effects that interruptions have on working memory also affect the ability to reason or plan. Information may be lost following an interruption. An individual may become confused and forget what was being considered. He or she may have to begin the planning or reasoning process again.

- **Rule-Based Errors**: If a person is about to apply a rule, is interrupted, and during the interruption the situation changes, he or she may return attention to the rule and apply it without considering the change in the situation.

- **Prospective Memory Errors**: Interruptions may cause a person to forget to perform some future intended action.

Related Principles:	All of the above sections (2.2, 3.1, 4, 6.1, 6.5, 6.7) contain principles which may help to minimize the negative effects of interruptions.
Relevance:	Interruptions are unavoidable in the instrument approach task. For this reason, the EIAP must be designed to minimize any detrimental effects of interruptions and must make it easy for the pilot to access information at the appropriate time.

6.7 Planning

Planning involves reviewing available information and reasoning to predict a future state, and then making decisions based on this prediction about what actions (also when and how) will be taken to reach a desired goal. All of the biases that people are subject to in reasoning and decision-making are also important in the activity of planning. Reason (1984) expresses one of the most important implications of the planning activity:

> "A plan is not only a set of directions for later action, it is also a theory concerning the future state of the world. It confers order and reduces anxiety. As such, it strongly resists change, even in the face of fresh information that clearly indicates that the planned actions are unlikely to achieve their objective or that the objective itself is unrealistic."

If a person puts a great deal of mental effort into creating a plan, the information in that plan will be highly meaningful and salient. If for any reason the plan must be altered, this meaningful and salient information may compete with the new information and lead to confusion or errors.

Layton, Smith, McCoy, and Bihari (1992) studied three different planning aids for flight planning. They found that pilots with fewer planning tools available to them chose more conservative options and studied the data more. However, pilots with fewer planning tools ran into trouble when the amount of data and number of possible solutions were greater. Subjects with multiple tools available were able to use them and did consider options other than the automatically generated one. However, the automatically generated plan may cause a shift of attention away from important facts that are required for making planning decisions.

Related Principles:	1, 2, 6, 19, 25, 26, 34, 35, 36, 48, 49, 50, 54. See also organization and grouping of information (7).
Relevance:	Pilots use instrument approach plates to "plan the approach." In general this is a fairly complex reasoning and decision-making task in which they must review several options and make a number of choices. Once the decisions have been made, the pilot may mentally (or verbally if there is more than one pilot) step through the plan. The pilot may set some "bugs" or markers, or may even take notes as a reminder of certain steps in the plan. Pilots are constantly subject to the possibility of a change in plan. At almost any time, ATC may request that a pilot give up the original plan and follow a new plan. The potential for confusion in such a situation is great. Principles for designing for planning are generally the same as those related to designing to match the pilot's model of the task.

6.8 Mental Arithmetic

Mental arithmetic is considered to draw most heavily on central-processing (or executive) resources (Boff, Kaufman, and Thomas, 1986; Eysenck, 1984). This suggests that the performance of mental arithmetic is likely to interfere with many different types of tasks and may even interfere with an individual's ability to allocate resources to other tasks effectively. Research by Hitch (1978) has shown that performance of mental arithmetic is improved when the auditory presentation is supplemented by a visual presentation of the problem or part of the problem. Hitch (1980) has also shown that errors are less frequent when the subject is required to articulate intermediate answers to the problem. Thus, the recommendation that reasoning problems be broken down into subgoals certainly applies to a mental arithmetic task.

Related Principles:	See section on integration of cognitive tasks (8.3).
Principle 58:	Reduce requirements to perform mental arithmetic.
Principle 59:	If possible, provide visual representations of any tasks which may be required.
Relevance:	Many aspects of the instrument approach task require pilots to perform mental arithmetic. Mental arithmetic is required for determining headings, times, and distances. Many of the heuristics that pilots use make these tasks easier; however, these heuristics are subject to biases and inaccuracies.

7. ORGANIZATION AND GROUPING OF INFORMATION

The organization and grouping of information has strong effects on how quickly and accurately information is processed by the humans. Proper organization and grouping can be used to reduce both perceptual and cognitive clutter and also may aid the pilot in planning and executing the approach.

7.1 Categorizing Information

Information that is grouped or categorized based on meaning will allow for the quickest and most accurate processing of information. Neisser (1976) reviews experiments that show that people can identify targets in a sentence faster when they are given the meaningful category (a fruit) to which the target belongs than when the target is defined literally (PEAR) or acoustically (pair). Grouping information that is related together speeds the recognition of the information (since one item provides context for another). The related information may also act as retrieval cues to help access any needed information from long-term memory. Woods (1985) suggests that information should be organized based on high level units and that task-meaningful units should be identified for organization. In addition, information that must be processed together should be grouped together.

A mental model for any given task should help to define meaningful categories and "task-meaningful units." Information which is grouped more closely in a mental model could be grouped on a display. Other methods such as card sorting may also help to identify what groupings or categories are meaningful to an individual.

Related Principles:	24, 48
Principle 60:	Use task analyses to determine groupings of information that are meaningful for the task, and to help in using this information.
Relevance:	To facilitate rapid retrieval and understanding of information on the EIAP, it must be presented in meaningful (to the pilot) groupings. Research available on the information requirements of pilots must be reviewed to determine the specific groupings. Task-meaningful groupings may be based on phase of flight, type of information, or, as suggested throughout this report, type of activity (planning vs. execution). Testing may be required to determine the most efficient means of grouping information.

7.2 Proximity

The second step in grouping information is determining how to represent a group of information. The Gestalt Laws of perceptual organization suggest that information will be perceived as a group through proximity, similarity, continuity, and closure. The law of proximity states that elements that are close to other elements appear as a group.

Care must be taken, however, in locating information elements close together. Other text or symbols close to a word prolong the time that it takes to recognize the word, especially if the information is located near the beginning of the word (Noyes, 1980). This is true if the relationship between the interfering information and the word is not meaningful. If the text in front of the word to be recognized was part of a meaningful sentence incorporating the word, search time may actually be faster.

Related Principles:	27, 28, 31
Principle 61:	Locate related information close together in space.
Principle 62:	Locate information that must be processed together close together in space.
Relevance:	The need for grouping of information on the IAP chart has already been discussed. The use of display proximity is an excellent and commonly used method of distinguishing groups. Pilots will expect related information to be located close together. One example of the difficulty of using proximity as a grouping mechanism is the current presentation of frequencies and identifiers. The frequency and identifier of a NAVAID run together with no distinctive separation, making it more difficult to distinguish them. Displaying identifiers in smaller text may help in distinguishing the two separate words and may help promote top-down processing of the information, while still allowing them to be grouped together through proximity.

7.3 Similarity and Coding

The law of similarity suggests that elements that resemble each other appear as a group. This is the basis for many coding schemes (coding is discussed in more detail in a later section). Color, lightness, size, and shape are all dimensions in which similar information elements can be made visually similar. Visual similarity is often used as a method of grouping when the information can not be located close together spatially. Using similarity as a grouping mechanism is subject to the following three conclusions:

- several similar elements may have to be present for the similar elements to appear as a group
- the fewer codes that are present on any given display, the better the grouping
- the more dissimilar group members and non-group members are, the better the grouping

Related principles:	7, 8, 13, 15
Principle 63:	Minimize the number of codes that are used for grouping.
Relevance:	The availability of color on electronic displays increases the ability to group information based on similarity. Current IAP charts use so many different symbols that there is very little grouping based on similarity. Each item of information on the display appears to be different from every other with only relations by proximity and closure (see below) apparent. Color coding may allow the presentation of information spatially while still providing some level of grouping information based on similarity of color. This makes the relationships between pieces of information much more apparent.

7.4 Continuity and Closure

The law of continuity states that elements tend to be grouped in a way that minimizes abrupt changes in visual direction. Information in a column appears in a group because there is no change in visual direction as the eye moves down the column. Lines or boxes around the column may not be needed since the information itself forms a visual line and adds to the clutter on the display. The law of closure states that elements arranged within a closed region are seen as a group. A closed region need not always be continuous lines. Shading may provide a grouping effect without adding to display clutter. The principles of continuity and closure are used in the display of information in tables. Grids in tables help people to match the information in a cell with the appropriate row or column label. Using finer (lighter) grid-lines than is used for information in the table may speed up the search of needed information since it allows the matching to appropriate rows and columns while adding very little display clutter.

Related Principles:	23, 26, 28, 31
Principle 64:	Display textual information in tabular form to take advantage of natural continuity.
Principle 65:	Where proximity and continuity are not enough to signify and group information, use the principle of closure.
Principle 66:	Minimize the amount of extra information added to a display to group information through continuity or closure.
Relevance:	The need for grouping information on EIAPs has already been discussed. The proper use of principles of continuity and closure will lead to organized display of information without adding display clutter.

7.5 Consistency

Consistency is an important principle in the organization of information on displays. Mangold et al. (1992) state that eye movement patterns are influenced by pre-existing knowledge of how charts are organized. Consistent location of information is especially important when an individual can only take a single glance at the display. The effects of expectation are especially powerful in this situation (Neisser, 1976).

Related Principles:	10, 12, 45
Relevance:	Consistent location of information reduces search time. In the current implementation of the plan view, the information is located spatially, with respect to earth reference; so it is not located consistently with respect to the display screen. Huntley's (1993) design incorporates a "briefing strip" that allows for location of important information both spatially and consistently. Pilots are especially susceptible to the effects of expectation during an instrument approach since limited time is available for them to view the EIAP.

7.6 Layering

Information on electronic displays also can be grouped in layers of information. Different groups of information can be available on separate pages or layers as a third dimension of spatial grouping. Layering of information also may be achieved by emphasizing one group of information while de-emphasizing another group of information on one screen. There are two major problems with layering information on separate screens on electronic displays: 1) there must be some control of the switching of layers and 2) some of the available information is hidden at any given time. For this reason Stokes, Wickens, and Kite (1990) suggest that, "in a realistic situation where operators must build a mental model of a system using relationships between and semantic properties of symbols, methods of highlighting such as contrasting, blinking, color switching may be better than removal or simplification strategies."

Endsley and Bolstad (1993) also provide recommendations on automatic filtering of information suggesting that any automatic filtering should:

1. Keep the pilot aware of the big picture
2. Incorporate pilot into control loop
3. Avoid filtering cues which may trigger long term memory stores

They remark that filtering is not a cure all--instead, information should be integrated into the needed format.

Related Principles:	19, 20, 21, 22, 23, 24, 25, 26
Principle 67:	Use layering or filtering of information only if putting all the information on one screen reduces search efficiency to an unacceptable degree.
Principle 68:	Use minimizing (in terms of size or brightness) over complete elimination of information as a decluttering technique.
Relevance:	The use of separate EIAP pages with different information should not be completely eliminated. Mykityshyn and Hansman (1992) studied pilots use of a prototype EIAP with decluttering mechanism which allowed maintenance or suppression of layers of information and showed that, in general, pilots were able to use it successfully. However, other methods of decluttering should be considered prior to using this method.

8. DIRECT PERCEPTION AND INTEGRATION OF INFORMATION

One of the most basic cognitive principles in the design of displays is to display information so that it can be directly perceived. The meaning of the information should be immediately obvious and should not require a number of mental transformations of the information.

Related Principles:	25, 54. See following sections on population stereotypes (8.2), cognitive tasks (8.3), display aircraft location (8.4), and symbols (9.1).
Principle 69:	Display information in its most integrated form so that it can be directly perceived.
Relevance:	The nature of the IAP task is not very direct. According to Ritchie (1988), pilots must depart from the conceptual framework of the primary task and "think in electronics." The cognitive task analysis reveals that the pilot must integrate information from a number of different sources. Much of the information, such as radio frequencies, has no inherent meaning in flying, geography, or navigation (Ritchie, 1988). If the IAP chart can do some of the integration of the information for the pilot so that information can be directly perceived, the instrument approach task could be made easier.

8.1 Symbols

Symbols should look like the objects they represent. If a symbol looks like the object it represents, there is no need to memorize a coding scheme. The meaning of the object is directly perceived. Taylor and Hopkin (1975) recommend simple symbol forms with high association value. Symbols that look like objects they represent also may shorten the time it takes for an individual to perceive the object since familiarity decreases the time it takes to perceive an object (Wickens, 1984). In addition, information that is provided to present a visual image should be presented as directly as possible as that visual image.

Related Principles:	10, 11, 16
Principle 70:	Use symbol forms that are highly associated with the object they represent.
Principle 71:	Present visual information in its most highly integrated form (as a picture of the image to be presented).
Relevance:	There are a number of symbols representing objects on IAP charts. The more a symbol looks like the object it represents, the easier it will be to remember what the symbol represents. One function of the EIAP is to help the pilot to set up expectations for what he or she will see as the airport approaches. These are visual images and to the degree possible should be presented visually. Huntley (1993) has demonstrated this principle in his improved paper IAP chart by moving the runway light acronyms to the top of the chart and adding a symbol that shows the runway light configuration the pilot expects to see. The pilot no longer has to decipher the acronym and then remember what that lighting system looks like to prepare for landing.

8.2 Population Stereotypes

The proper use of population stereotypes also facilitates direct perception of information. Population stereotypes such as red for danger and blue for water are so well learned that perception of them is direct. People already know the meaning of population stereotypes and do not have to memorize yet another coding scheme. Any time a population stereotype can be used instead of some arbitrary code, perception will be more direct. In contrast, if a visual representation violates a population stereotype, perception of the information will be slowed and errors may result.

Principle 72:	Take advantage of common population stereotypes.
Principle 73:	Never violate a population stereotype.
Relevance:	If population stereotypes are used properly, they can be very beneficial to an EIAP. They may limit the number of new coding schemes a pilot has to remember (or look up). Care must be taken not to violate any population stereotypes. The population of pilots and any stereotypes they may have based on flying experience or other instrumentation in the cockpit should be reviewed carefully in the determination of color coding, symbols, and controls of EIAPs. In addition, population stereotypes vary across societies, and international differences must be considered.

8.3 Cognitive Tasks

Many cognitive tasks such as reasoning, decision-making, planning, and mental arithmetic may be reduced through the use of electronic displays. Anytime the electronic display is capable of integrating the information to be provided to the user into the form that the user needs, the integration should be performed. This reduces cognitive clutter and workload for the user.

Related principles:	48, 49, 53, 54, 55, 58, 59
Principle 74:	Automatically (if possible) determine the information that is relevant to a given aircraft and situation so the pilot does not have to choose from among a number of different information elements.
Principle 75:	Perform any mental arithmetic automatically for the pilot and display only the necessary final form of the information.
Principle 76:	Use abbreviations or acronyms which are directly meaningful to the pilot and do not require memorization or interpretation.
Relevance:	There are a number of cognitive tasks that a pilot must perform on the information provided by the IAP that can be integrated with an EIAP. One example is the display of minimums in tabular form. The pilot is required to determine his or her aircraft category and find the appropriate minimum within the table. An EIAP provides the opportunity to automatically (or through pre-flight input) determine the aircraft category and display only the needed information. As another example, the electronic chart could automatically detect the aircraft's speed, calculate the time to the missed approach point, and display it as a countdown clock (that could be automatically updated as the aircraft speed changes). Currently the pilot has to estimate his average speed, interpolate from a table of speeds and times to get the correct time, and then monitor his timer. In addition, the use of acronyms which are not familiar to the pilot will require extra processing to determine their meaning.

8.4 Display Aircraft Location

Possibly the most helpful information integration that an electronic chart may be able to provide is the display of the aircraft's current location. O'Hare and Roscoe (1990) state that map displays that show the position of the aircraft yield improvements in a pilot's ability to maintain geographic orientation, plan complex routes, and control position. The pilot no longer has to assimilate information from various instruments to determine the aircraft's location in relation to the map display. In addition, the pilot is able to orient quickly to his or her location and can easily move from that position on the map to attain needed information.

Principle 77:	Display the location of the aircraft on the EIAP.
Relevance:	One of the most difficult tasks involved in the instrument approach task is keeping track of where the aircraft is located. In fact, one instructor stated that his students did not have trouble keeping track of where they were going; they had trouble keeping track of where they were. Mykityshyn and Hansman (1992) tested a system that displayed real-time aircraft location and every pilot commented that the depiction by an aircraft symbol of the real-time position of the aircraft provided a tool for error reduction.

9. CODING

All displays must deal with issues of coding. Coding is the representation of information with some symbol, color, or other means. The most common method of coding is through text. Language is a code used to represent information in our environment. According to Thimbleby (1990) there is a well developed sense of composition (rules, etc.) for textual interaction but there is not one for graphical interaction. One problem with text, however, is that it often takes more space than symbols. Another problem with text is that some information (such as spatial information) is more suited to a graphical display.

Williams (1966) presents a list of the some of the different methods of coding information and the improvement in search time that is gained through their use:

Table 1. Mean detection time for targets in Williams' visual search experiment

CODING	TIME (sec)
Number only (control: present in all conditions)	22.8
Shape	20.7
Size	16.4
Size and Shape	15.8
Color	7.6
Color and Shape	7.1
Color and Size and shape	6.4
Color and Size	6.1

Obviously, color is a great enhancer of visual search. The implications of different methods of coding are important in the design of EIAPs since a great deal of information must be represented. The text includes the use of acronyms which may or may not be learned to the point that they can be directly perceived by the pilot.

9.1 Symbols/Shape

The most basic principle in symbol design--provide symbols that directly convey the meaning of the object they represent--has already been discussed. Standardization of symbols across other displays also will reduce memory load and facilitate fast recognition of symbolic information. Minimizing the number of symbols used in any system will also reduce memory requirements for a user. In some cases the determination of whether to use text or symbols may be a question. Pictorial representations are less disrupted by degraded viewing conditions, may take up less space than text, and in many cases can be perceived at least as quickly as text (Ells and Dewar, 1978). However, one must be careful not to always choose a symbolic representation over text. If the object or meaning can not be represented directly by a symbol and is represented by an arbitrary symbol, it will add to the pilot's memory load. Any introduction of new symbols should be evaluated for its effect on the entire task.

The use of representative symbols in electronic displays can cause difficulties because of resolution problems. However, electronic displays also may provide quicker access to legends or definitions of the object presented. For example, electronic displays have the capability of allowing an individual to select an object, then present information about that object for a short period of time.

Related Principles:	10, 11, 16, 38, 70, 71
Principle 78:	Standardize symbols so that they are consistent between different EIAP designers and consistent with other cockpit displays.
Principle 79:	Minimize the number of symbols on the display.
Principle 80:	Evaluate each information element to determine if a pictorial or symbolic representation accurately represents the information. If the meaning can be made inherent in a symbol, or space constraints preclude the use of text, use a representative symbol, if not, use a textual representation (see section on language/text).
Principle 81:	Provide a fast and easy method of determining the meaning of symbols.
Relevance:	Current paper IAP charts require pilots to memorize the most common symbols and refer to a legend for other symbols. The design of symbols on EIAPs will be even more important than on IAPs due to the limitations mentioned above. Standardization and the use of an electronic legend may eliminate some of the problems associated with having a great number of different symbols.

9.2 Size

Size coding may be used to emphasize information of greater importance by displaying it in a larger size. Increased size may be used to highlight information that is in the current "layer." For a code expressed by size, the ideal is no more than three different sizes, while five sizes is considered the maximum (Potash 1977).

Related Principles:	16
Principle 82:	Use no more than three different sizes of symbols if size is used as a coding mechanism.
Principle 83:	Increased size makes an object more salient; therefore, objects which are most important and necessary for the current phase of a task should have greater size.
Principle 84:	Present important textual information in a larger size than other textual information.
Relevance:	Size may be used on EIAPs to distinguish between primary and secondary information. If decluttering through emphasizing and de-emphasizing is used, distinction by differences in size would be an appropriate tool for this.

9.3 Color

Pilots in a study by Mykityshyn and Hansman (1992) found that color had a decluttering effect. It allowed them to "mentally eliminate" information of less interest. "Quite modest uses of color may incur clutter, distraction, or delay, particularly if the color serves no immediate purpose; but color, used appropriately, can reduce clutter and a very large number of discriminable colors can be used to good effect, as in some computer graphics and maps" (Hopkin, 1992). Hopkin warns that color coding has the problem of visual dominance over other codings. Color codings are treated as operationally significant. People will recognize the color code of an information item before the shape or size of the item. It is important to use color coding redundantly with other methods of coding and to use it consistently.

Hopkin (1992) states that it is important to consider aesthetics of colors since too much color and/or garishness may draw attention to the coding and away from the information. Too much saturation, too many colors, excessive contrast in brightness, unadjustable saturation or brightness, uncoordinated colors, colors that don't blend with other displays, and colors that are not needed all lead to potential color display problems.

The objective of color is to "improve the efficiency of information portrayal for the tasks and to facilitate the discrimination of required information categories" (Hopkin, 1992). The advantages of color coding include faster and more accurate performance, fewer errors and omissions, and more controlled and directed search. The use of color displays may also be more easily taught, learned and remembered. Historically, color has been used extensively on maps and charts. Cartographers are familiar with and knowledgeable about color. Hopkin (1992) suggests that "Color is essential to help to resolve cartographic information categories . . ."

The usefulness of color increases with increasing information density and complexity (Taylor, 1985). The use of color should coincide with population stereotypes so it matches the existing expectations of pilots. There are two different sets of expectations that should be considered when determining the color coding to be used on an electronic display of cartographic information in the cockpit. The table below lists the two different conventions--one for electronic display of aircraft cockpit information and one for display of cartographic information--that should be considered before determining a color scheme.

Table 2. Comparison of electronic cockpit and cartographical color conventions

COMPARISON OF ELECTRONIC COCKPIT AND CARTOGRAPHICAL COLOR CONVENTIONS		
COLOR	**ELECTRONIC COCKPIT CONVENTION (Wykes and Spinoni, 1988 in Hopkin, 1992)**	**CARTOGRAPHIC CONVENTION (Robinson, et al. 1978 in Grossman, 1992)**
White	Fixed, non-dynamic information	Ice, high elevations
Green	Positive indication or instruction and cross-referencing of data	Vegetation
Red	Urgent warnings or threats	Important items, roads, cities, hot
Amber-Yellow/Tan	Less urgent warnings or threats	Dryness, medium temperature, medium elevation, lack of vegetation
Blue	Area fill and display structuring	Water, sky, cool
Cyan	Visual separability	
Brown	Pictorial representation of ground	Land, mountains, warm

Related Principles:	15, 16, 22. See also Hennessy, Hutchins, and Cicinelli (1990), compilation of 74 guidelines for the use of color on electronic display.
Principle 85:	Use color consistently throughout the EIAP.
Principle 86:	Use color codes that are consistent with existing standards of either cockpit electronic displays or topographical conventions.
Principle 87:	Minimize the number of color codes used. For casual users or when color is used for absolute discrimination, limit the number of colors to four. For experienced, long-term users or when color is used for comparison, up to seven colors may be used (Hennessy et al., 1990).
Principle 88:	Maximize the use of display colors low in purity (e.g., pink, cyan, magenta, and yellow) (Hennessy et al., 1990).
Principle 89:	As the number of colors increases, increase the size of the color coded objects (Hennessy et al., 1990).
Principle 90:	When fast responses are needed, use highly saturated colors (e.g., red or blue) rather than yellow (Hennessy et al., 1990).
Principle 91:	Use color codes that are redundant with other codes (such as shape or text).
Principle 92:	Always code alphanumeric information in red, yellow, or white, and confine light blue to large background areas (Hennessy et al., 1990).
Principle 93:	Use colors that are maximally discriminable (40 units in the 1976 CIE LUV space)(Hennessy et al., 1990).
Relevance:	The usefulness of color in complex, high information density displays makes it potentially beneficial for use on EIAPs. The proper use of color has the ability to declutter and speed visual search. The use of color on EIAPs may make up for the lack of resolution provided by electronic charts.

9.4 Other Methods

Electronic displays provide designers with the opportunity to use other methods of coding such as highlighting (or bolding), reverse video, and blinking. These methods of coding should be used sparingly since they may slow down a pilot's ability to retrieve unhighlighted material. Novel, unexpected stimuli are best used for warnings or cautions since they both draw attention to themselves and are well remembered (Eysenck, 1984).

Related principles:	15, 16, 22
Principle 94:	Use other methods of highlighting such as bolding, reverse video, and blinking sparingly (possibly only for warnings and cautions).
Principle 95:	If these methods of highlighting are used for warnings or cautions, provide the pilot with the ability to turn them off.
Relevance:	It may be possible to provide pilots with the ability to highlight a group of information that is currently in use by adding a little brightness (or by dimming current information that is not in use) as a decluttering mechanism. This may provide a "layering" of information. Any method of grouping information such as this should have a very easy control and should also provide a simple control to return the display to its original state.

10. DISPLAY OF TERRAIN INFORMATION

The information that has been presented in this report has a number of implications for the display of terrain information. In general, terrain information is spatial information and, for that reason, a spatial display that provides pilots with a direct comparison of the altitude of the aircraft and the elevation of terrain would be the most integrated display of terrain. This suggests that rather than displaying terrain in a plan view (bird's eye view of the ground), it may be more appropriate to display terrain in a profile view that provides a visual representation of altitude. A profile view that displayed terrain information would also have to display the vertical location of the aircraft and would be required to be dynamic so that the display of terrain was always current with the location of the plane.

If current, dynamic profile elevation information is unavailable, color may be an ideal coding mechanism for the display of terrain. Current methods of displaying terrain information on paper maps with contour lines or with gradually changing colors also provide some integration of terrain information. Some of these methods should be attempted on electronic displays to determine their feasibility.

Research on decision-making and reasoning suggests that humans will only look to one or two sources of information. If terrain is presented in several different ways (currently through spot elevations, minimum sector altitudes, step-down minimums, and ATC minimums), pilots are likely to consider only one or two of the sources. It makes sense, then, to determine which source provides the most accurate and comprehensive terrain information and eliminate other sources so that pilots do not place too much emphasis on the wrong source or ignore the best source of information. Friend (1988) complains that the presence of spot elevations and obstacles may lead pilots into believing the obstacles shown are the only obstacles in the approach area. Indeed, pilots are prone to rely too much on such information. Pilots will do the same with terrain information provided to them by ATC (this is the most likely source they will use since it is prominently displayed and they are not required to search for it). This explains Kuchar and Hansman's (1992) results in which pilots avoided terrain only 3 of 52 times when given erroneous vectors by ATC.

Related principles:	69
Principle 96:	Choose the one or two most accurate and comprehensive methods of displaying terrain on the EIAP and eliminate all others.
Principle 97:	Consider displaying terrain information visually in a dynamic profile view (the utility of this principle may not be realized until three-dimensional displays are available).
Principle 98:	Be sure that all terrain information is always accurate.
Relevance:	There is considerable discussion about the display of terrain on EIAPs. In determining the best method to display terrain, the purpose of the display must first be determined. If the terrain is to be displayed to give the pilot a general feel for the surrounding terrain, then it should be displayed visually or graphically through the use of color or contour lines or even an actual scaled depiction of the terrain in a vertical dimension. Obstacles which may provide visual reference should be shown with a representative symbol. If the reason for providing the information is to give the pilot a minimum altitude that he or she must not go below (for collision avoidance--with terrain or other aircraft--or obstacles) then an actual minimum should be provided. This information may also be color coded but should be standardized throughout all cockpit elevation displays (for example if blue is to indicate 5000--10000 feet then altimeters should also show a blue bar in the range of 5000--10000 feet). Whatever method is chosen, it must be understood that pilots will use the information that is most easily accessible and will rely on it solely unless forced to do otherwise (through procedures, checklists, or some other means).

11. LANGUAGE CONSIDERATIONS

Hawkins (1987) provides several recommendations for the use of language on displays. he suggests that shorter and more familiar words will be understood more quickly and easily. Shorter sentences (less than 20 words is best) are preferred over longer sentences. Careful attention should be paid to the meaning of sentences. Sentences should be arranged for correct understanding and should not allow any ambiguity. In general, people respond to and understand positive, active language more easily than negative, passive language. One other consideration is the use of acronyms and abbreviations. Acronyms and abbreviations should be used minimally since they often require more processing to understand their meaning.

Principle 99:	Verify that sentences or phrases are clear and unambiguous.
Principle 100:	Use short and familiar words whenever possible.
Principle 101:	Use the active voice and positive statements.
Principle 102:	Limit the use of acronyms and abbreviations.
Relevance:	The use of language on EIAPs will probably be limited to short phrases, words, acronyms, and abbreviations. It is important to make each of these as meaningful and unambiguous as possible, even if this requires a short phrase instead of just one word. Paper IAPs currently use many acronyms and abbreviations. Some acronyms and abbreviations are immediately understood by pilots since they are frequently used. In fact, for some acronyms pilots may know only the acronym and not the original phrase it represents. In those cases, the use of acronyms is preferred.

12. DYNAMIC DISPLAYS

12.1 North Up vs. Track Up

One of the issues involved in the use of dynamic geographic displays is the choice of reference frame for the display. Based on the principle of integration of information it is suggested that a display providing a reference frame that is track up, (ego-centered) may be preferred to a display that providing a north up or world-centered reference frame. Such a display would not require any mental rotation of information to the reference frame of the individual. However, there are a number of other issues that should be considered before choosing to use an ego-centered, track-up reference frame.

Stokes, Wickens, and Kite (1990) state that there are three principles that should influence the choice of reference frames:

- Constancy of Reference Frames: The choice of reference frame should remain constant. Inconsistent reference frames may lead to errors.

- The Principle of the Moving Part: The choice of reference frame should be such that the part that the user perceives as moving should be the part that actually moves. For navigational displays, this suggests that the initial turn of the aircraft should be reflected by rotation of the aircraft symbol in the direction of the turn rather than rotation of map in opposite direction. The effectiveness of one over the other may be a function of complexity of path.

- Principle of Frequency Separation: Roscoe (1980) suggests the use of a "frequency separated" display. This display shows the conventional moving horizon in conjunction with an indication of roll rate and acceleration with the aircraft symbol.

Aretz (1992) proposed another integrated technique. The "visual momentum" technique provides a wedge on a north-up map that indicates the area which is within the pilots ego-centered view.

Other researchers suggest that the movement of the display should be determined by the type of task involved. Track-up displays may be better for navigation, tasks that require route knowledge, or for use when one is lost (Aretz, 1991). North-up displays may be better for a greater variety of tasks including planning (Harwood, 1989).

Related Principles:	5, 3, 69, 77
Principle 103:	Maintain a consistent reference frame within the EIAP.
Principle 104:	Provide a north-up reference frame for planning purposes.
Relevance:	The instrument approach task requires survey knowledge during the planning part of the task, and route knowledge during the execution of the task. This would indicate that a North-up map showing real-time aircraft position would be best for planning of the task. During actual execution of the task, either a route list (an ordered list of specific information), or a track-up display would be recommended. Since consistency of reference frame is required, a north-up display that shows real-time aircraft position (possibly utilizing Aretz's (1991) visual momentum technique) is recommended (this coincides with Mykityshyn and Hansman's (1992) results that pilots preferred this type of display over a track-up display). If a track-up display is used for the execution of the task, it is important that this display and a north-up planning display be distinctively different (different shape, size, color of background) so that there is no likelihood that a pilot will confuse the two displays. A route list of execution information is preferred for this situation.

12.2 Pilot Control of Displays

A number of issues related to pilot control of displays already have been discussed. Decluttering techniques were discussed in the section on Layering. Endsley and Bolstad (1993) suggested that decluttering should be under pilot control. The instrument approach task is so complex and situation dependent that it would be impossible to predict what information a pilot needs at any given time. "The decision to allow a pilot to choose what and how much information should be displayed on a particular panel may well decrease visual workload, but it may impose unwanted workload costs on two other pilot resources: those related to memory and to responses" (Stokes and Wickens, 1988). The pilot must now remember what is not being displayed and how to obtain it. Also, continuous display of information acts as a reminder that it must be inspected, this reminder may be eliminated if the pilot is allowed to configure the display. For these reasons, if it is possible, the display of information should be limited to one screen (with potential decluttering through highlighting or minimizing as discussed). However, since electronic displays do not have the resolution available on paper, it may be necessary to display IAP information on separate screens. If this is the case, basic design principles related to controls and actions must be followed.

Thimbleby (1990) states that reducing the number of controls may make an interface look more simple, but if this requires functions to be hidden, then it is actually more difficult. For a display in which speed and ease of selection is required, it is important that all controls be visible and simple to operate.

Related Principles:	67, 68
Principle 105:	If possible, display all information on one screen.
Principle 106:	Provide decluttering techniques that do not remove information completely.
Principle 107:	If information is present on more than one screen, make visible the control to switch screens.
Principle 108:	A cue to what information is on hidden screens should be present at all times.
Relevance:	There is a possibility that EIAPs will require that information be displayed on more than one screen. The method to retrieve other screens (including such screens as legends) should be visible and obvious. Touchscreen buttons with meaningful labels is an example of an easy and visible control. Controls for potential decluttering mechanisms are subject to the same principles.

13. CONCLUSIONS AND RECOMMENDATIONS

This paper presents forty-six cognitive issues and 108 design principles and provides a general introduction to the field of cognitive psychology and the application of well researched cognitive issues to the design of EIAP displays. However, the principles are based on general research literature and have not been validated within the specific domain of EIAP design. There may be unknown or unexpected interactions among many of the design principles. For this reason, these principles should not be followed to the letter by designers of EIAPs without further validation.

The ultimate goal of this project is to create a handbook to be used by designers and certifiers of EIAPs. While this paper provides a comprehensive research base from which to create such a handbook, further steps are required to design an easy-to-use handbook for designers and certifiers. First, the information in this paper must be incorporated with current research in the area of human-computer interaction to organize information in a manner that is useful to designers, i.e., by design features. Based on the information in this document the following major design issues require more specific design guidelines with pictorial examples of those guidelines:

- **Symbol Design**: Discussions dealing with memory, visual search, pattern recognition, attention, direct perception of information, and coding all point to the need for good symbol design on EIAPs.

- **Grouping and Coding of Information**: More specific pictorial examples are needed to demonstrate grouping and coding principles. Information available on pilots' information requirements and information currently being gathered at NASA-Langley (Ricks and Rogers, 1993) on pilots' concepts of grouping the information should be used in these examples.

- **Orientation of Information**: A number of design issues related to the orientation and scaling of information must be addressed.

- **Control of Clutter**: This document has suggested a number of methods of controlling clutter. The use of layering, highlighting, or zooming introduces design difficulties that may require specific guidelines.

- **Pilot Control of Functions**: The use of functions on an EIAP such as those mentioned in the control of clutter will require pilot control. More specific methods of selection of information on an EIAP must be presented (with pictorial examples) and guidelines must be made available for their use.

- **Design for Planning**: Pilots' use of the IAP for planning purposes has been made clear throughout this research. Examples of displays that provide good planning design are needed for clear understanding of design guidelines.

- **Minimizing Errors**: Methods of minimizing errors such as providing sequence reminders must be investigated.

- **Minimizing Effects of Interruptions**: The effects of interruptions is a major issue in EIAP design. Methods of minimizing these effects must also be investigated.

- **Integrating Information**: Examples showing the differences between integrated and non-integrated information should be presented to designers. Current paper charts should be reviewed at every opportunity to integrate information. The display of the aircraft location on the chart must be investigated in more detail to provide true design guidelines.

- **Display of Terrain Information**: Specific guidelines related to the display of terrain information should be researched and provided to designers. Issues such as decluttering by removing terrain information must be addressed.

The next phase of this project will address these and many other specific design issues. Specific guidelines that designers and certifiers can use will be provided along with pictorial examples for their use. Early and comprehensive research into these issues will provide designers and certifiers with the tools needed to create safe and usable electronic instrument approach procedures.

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APPENDIX A

Summary of Current Practices, Operational Requirements and Potential Cognitive Implications

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APPENDIX A CONTENTS

Section		Page
1.	INTRODUCTION	A-1
2.	COGNITIVE TASK ANALYSIS	A-2
3.	THE INSTRUMENT APPROACH TASK	A-3
4.	FACTORS THAT AFFECT THE INSTRUMENT APPROACH TASK	A-6
5.	INFORMATION REQUIREMENTS OF THE INSTRUMENT APPROACH TASK	A-11
6.	COGNITIVE IMPLICATIONS OF THE APPROACH TASK	A-14
7.	DESIGN GOALS FOR INSTRUMENT APPROACH PROCEDURE CHARTS	A-16
8.	THE CURRENT DESIGN OF IAP CHARTS	A-17
9.	COGNITIVE ISSUES IN THE DESIGN OF IAP CHARTS	A-19
10.	CONCEPTUAL GRAPH STRUCTURE METHOD AND RESULTS	A-26
11.	APPENDIX REFERENCES	A-32

1. INTRODUCTION

As a first step in the development of a Cognitive Handbook for the Design of Electronic Displays of Instrument Approach Procedure (IAP) Charts, the current practices and operational requirements of the instrument approach task are reviewed. In order to identify the cognitive issues that are pertinent to the design of electronic IAP charts, it is necessary to have a thorough understanding of the task that the charts are designed to facilitate. This knowledge can be gained in the following ways:

- Review the current design of IAP charts
- Review instrument flight training manuals and videos
- Talk with pilots and perform instrument approaches on simulators
- Review articles written by pilots about instrument approaches and IAP charts
- Review research on potential improvements to current IAP charts (both paper and electronic)
- Review research on the information requirements of the instrument approach task
- Perform a Cognitive Task Analysis of the instrument approach task
- Ride jumpseat in aircraft that are making instrument landings

This document provides a summary of the information obtained through completion of the above tasks, and points out cognitive implications that have been identified during the collection of this information.

2. COGNITIVE TASK ANALYSIS

Several methods of Cognitive Task Analysis were reviewed to determine the most appropriate method for the instrument approach task. All of the methods involve some type of verbal protocol or structured interview to elicit knowledge from experts. For a complex task such as the IAP user's task, researchers (Redding, Cannon, Lierman, Ryder, Purcell, and Seamster, 1991 and Shlager, Means, and Roth, 1990) have videotaped the experts performing the task and then elicited information from the experts while viewing the videotapes. Several researchers (Redding et al., 1991, Thordsen, 1991, and Gordon, Schmierer, and Gill, 1993) have demonstrated that creating a graphical representation of concepts, goals, and actions following an initial interview helps in eliciting further knowledge from experts. Thordsen (1991) also suggested that, after acquiring task knowledge from experts and creating a graphical representation, asking experts to describe a critical incident allows the researcher to get an overview of the normal situation while also seeing how unusual situations fit into the graphical representation.

A composite of these methods was used in analyzing the instrument approach task. Various sources such as instrument rating manuals and instrument training videos were reviewed to understand how the task is described to novices. Interviews with subject matter experts (SME) (mostly general aviation) were conducted. Simulations of the task were run, observed, and discussed with an SME. Literature on the information requirements of the approach task was also reviewed. An attempt was made to use the Gordon et al. (1993) methodology to create a Conceptual Graph Structure of the instrument approach task. Although difficulties were encountered in following this methodology (the methodology and results are presented in Section 10), the knowledge gained through the exercise added a great deal to the following discussion. The results of the total effort are presented below as a description of the instrument approach task, a discussion of the many factors which affect the task, and a discussion of the information requirements of the task.

3. THE INSTRUMENT APPROACH TASK

An instrument approach procedure is required any time a pilot must make a landing in conditions which prohibit visual navigation to the airport. Often instrument approach procedures are used as a navigation aid even when visual navigation is possible.

The instrument approach task actually begins when the pilot is constructing his or her flight plan. At this time the pilot reviews the weather conditions at the departure site, en route, at the landing site, and at an alternate landing site. The pilot will review the different instrument approach procedures available at the landing site and at an alternate. The pilot also will consider the terrain around the departure site, the landing site, and the alternate. The pilot may select a Standard Instrument Departure (SID) and may review the Standard Terminal Arrival Routes (STAR) to determine which arrival route to the approach he or she will be following. The pilot also will be planning the flight route, climb, descent, and fuel consumption.

A great deal of prior knowledge is required in the planning and flying of an instrument flight. The pilot must be familiar with navigation and the Instrument Flight Rules (IFR). This includes the knowledge of Air Traffic Control (ATC)--what to expect from an Air Traffic Controller, when to expect it, and how to respond. The pilot must also be familiar with the various NAVAIDs to be used along the route and during the approach to landing. These NAVAIDs include VHF/UHF communications, very high frequency omnidirectional range (VOR) stations, distance measuring equipment (DME), instrument landing systems (ILS), automatic direction finders (ADF), marker beacons, flight management systems (FMS), automatic communication and reporting systems (ACARS), satellite communications (SATCOM), and global network satellite system (GNSS). The pilot must know how each system works, how to control the avionics associated with the system, and how to interpret the cockpit displays pertaining to these systems. The systems a pilot must be familiar with will be dependent on the aircraft and its equipment and the approaches the pilot plans to fly.

When the pilot is ready to take off, he or she will follow the instructions provided on an SID if instrument departures are available for the departing airport, or he or she will follow specific instructions provided by ATC. The pilot then flies toward the selected destination. When the pilot nears the destination and is ready to prepare for descent, the pilot sets up the approach. Each pilot may prepare for the approach by performing actions in a slightly different order, and will perform these actions as opportunity permits. The actions that a pilot should perform during this preapproach phase are as follows:

- When in close enough range to receive automatic terminal information service (ATIS) (if it is available), tune one of the radios to the ATIS frequency (provided on the approach plate for the airport) to receive up-to-date airport information--weather (winds and visibility), the active runway, the approaches in progress, the ATIS information designator code, and any other pertinent information.

- Once you know the probable approach procedure, select an appropriate STAR and IAP.

- Use the information provided by ATIS on the winds and visibility and the information on the IAP chart to compute the landing speed, approach times, and approach and missed approach power settings.

- Review the IAP to become familiar with the approach in progress. This includes planning the approach and becoming familiar with the airport and surrounding area.

- If applicable, brief the crew on the approach procedure.

- Execute the descent checklist.

- Use information from the appropriate approach plate to pretune communication and navigation radios.

- Review the fuel state.

- Listen to the radio to learn traffic flow, weather and probable speed restrictions.

- If the flight is a commercial flight, comply with company radio arrival procedures.

- Communicate with ATC--state intentions, state information designator of last review of ATIS, and listen to, repeat, and state intentions to comply (or not and why) with instructions. The ATC may announce that the approach has changed and require that many of the above actions be repeated.

While the above actions are being performed, the pilot has also been flying the aircraft--maintaining attitude, altitude (descending), and heading toward the final destination. Eventually, control of the aircraft will be handed from center to approach control. At this time, the pilot will be navigating the aircraft toward the initial approach fix by means of NAVAIDs through published approach procedures and onboard avionics or by radar vectors provided by ATC. The pilot will be controlling speed as required by aircraft performance limits, speed restrictions set by ATC, concern for passenger comfort, and intentions filed in the flight plan.

Any time after the handoff from Center to Approach Control, the aircraft may be (a) cleared for the approach or (b) cleared to a fix (clearance limit) short of the airport of intended landing, told to hold, and told when to expect further clearance. In general, if the aircraft is not cleared for the approach, some of the following tasks should be performed, as appropriate, to the clearance limit fix; if the aircraft is cleared for the approach, all of these tasks must be performed:

- Navigate to initial approach fix identified on IAP chart (or fly specified vectors).

- Intercept and fly inbound course (or curved path) identified on IAP chart.

- Intercept and fly descent profile specified on IAP chart (non-precision approach) or glide slope (precision approach).

- Configure aircraft for landing--adjust landing gear, flaps, spoilers, lights, airspeed.
- Execute landing checklist.
- Reconfirm minimum descent altitude (MDA) (non-precision approach) or decision height (DH) (precision approach) specified on IAP chart.
- Review missed approach procedures, especially the initial pull-up and course instructions.
- Reconfirm winds and aircraft performance limits.
- Contact tower ATC and receive landing clearance.
- Acquire visual contact with the runway environment at or before DH or MDA, then continue to land or perform a missed approach.
- If landing--flare aircraft, reduce thrust, reverse thrust, deploy spoilers, brake as required, turn off the active runway and taxi to gate or parking.
- If visual contact is not acquired, execute missed approach--add climb power, pull-up, turn to missed approach heading. When clear of runway, retract landing gear, apply flap schedule, follow missed approach course and altitude instructions.
- Navigate to missed approach fix. Enter holding pattern or proceed as directed to another approach attempt, holding, or execute flight plan to alternate.

4. FACTORS THAT AFFECT THE INSTRUMENT APPROACH TASK

The description of the instrument approach task provided above is very general. It is impossible to provide a specific description of an approach task without identifying the many factors that affect the task. Factors such as aircraft type, weather conditions, pilot differences, and many others make the task uniquely different for every pilot, aircraft, airport, and given day or time.

4.1 Approach Type

Different types of approaches have different information requirements and different levels of difficulty. For example, a precision (ILS) approach allows the pilot to monitor a glide slope display to maintain altitude requirements. This frees the pilot from having to refer to the approach plate for stepdown altitudes and from having to determine distance from the Localizer (through a DME or by monitoring the passage of time). The pilot only has to "center the needles" (localizer and glide slope), watch for the airport and watch for his altitude to reach the decision height. While this is not an easy task (centering the needles is easier said than done), it is less difficult than the mental gymnastics that may be required when performing an NDB approach that uses vector intersections as fixes.

4.2 Approach Complexity

Within each approach type there are also varying levels of complexity. Intersecting and flying a DME arc may be more difficult than a procedure turn. A course reversal in a holding pattern is another complex approach. Different approaches also will lead to different kinds of complexity. For example, in an ADF procedure the pilot must cognitively account for wind. Therefore, a radar vector to a final approach may seem simpler; however, following a radar vector provided by ATC makes it more difficult for a pilot to maintain situational awareness.

4.3 Number of Pilots

A single pilot will have to perform all of the actions involved in the approach task whereas in a dual pilot situation some of the workload may be shared. In a dual pilot situation, additional tasks such as communication and coordination between pilots may make the task very different from the single pilot's task.

4.4 Weather

Because instrument approaches are performed when visibility is poor, it is common for the approaches to coincide with poor weather. High winds, turbulence, wind shear, icing, and storms all make the instrument approach task more difficult by increasing the number of things the pilots have to attend to, and thereby increasing workload. In most of these cases the task is made more difficult because the task of flying the airplane is more demanding and pilots have less time to concentrate on approach information.

Weather also can alter how the approach is planned, or even whether or not the cleared approach can be accepted. For example, if a sloping ceiling (higher on the approach than at the airport) is reported on a non-precision approach, the pilot may decide to step down to MDA rather quickly after passing the final approach fix, then level out (as opposed to a gradual descent, approximating a glide slope which would be more comfortable for passengers). The crosswind component and reported braking action (wet or icy conditions) influence whether or not a given runway can be accepted. The approach lighting and touchdown zone configurations become particularly important in very low visibility conditions since they may be a pilot's first visual cues.

4.5 Time of Day

Many instrument approaches are flown at night, when it is difficult to read information inside the cockpit. Instrument approaches during the day also can affect the instrument approach task since weather conditions may cause the cockpit to be overly bright or subject to glare.

4.6 Air Traffic and ATC Instructions

The amount and type of air traffic can also negatively affect the instrument approach task. In addition to adding more things for the pilot to worry about, it may also cause an increase in Air Traffic Control workload. This may increase the likelihood of an ATC mistake and make it more difficult for the pilot to communicate with ATC.

ATC is also likely to place speed restrictions or demands (usually requiring a pilot to fly at a speed which is higher than optimum) which affect the difficulty of th task. At a faster than optimum speed the pilot has less time to prepare for the approach and is required to fly the approach with his or her aircraft in a less familiar configuration. Ultimately, it is the pilot's choice to deny such ATC requests. Unfortunately, less experienced pilots may lack the confidence to deny ATC instruction and they are the pilots who are most at risk in this situation.

4.7 Avionics Suites

The avionics suite in the aircraft influences the task difficulty, and workload, and may interact with IAP design. At the low end of complexity there are single pilot, general aviation aircraft in the ATC system; at the high end are the "Glass cockpit" aircraft that are equipped with state-of-the-art avionics. Most aircraft that will use electronic IAP displays would probably be equipped with a modern, redundant Nav-Comm suite (including HSI), autopilot, and probably color radar. At the low end, the avionics might be operated manually, perhaps with a low-cost Flight Management System (FMS); at the high end, dual FMSs would be standard equipment. The FMS usually is programmed with the full flight plan from takeoff to touchdown. This is done manually in many systems today, but in the near future, the programming (vertical and horizontal navigation from the beginning of flight to landing) will be loaded via Datalink and/or Gatelink.

The complexity of the avionics suite may influence IAP chart design in at least two ways: first, in a relatively manual low-end aircraft, data will be derived from the IAP chart by the pilot and commitred to memory, written, or stored somewhere convenient, such as on take-off or landing data cards, reference bugs on various instruments, altitude alert controls, and even on unused radio frequency displays. Thus the pilot has to extract the information, classify it, store it for immediate or future use, and remember where it is stored. Thus, the sequencing and arrangement of information on an electronic IAP chart is important for convenient retrieval at the proper times during the descent and landing. It may also be possible for a properly designed IAP chart to reduce the requirement for transfer of data to the other places (memory, cards, bugs, etc.) for quick use later.

Second, at the high, completely automated end, much of the IAP critical information (frequencies, courses, waypoints, distances, aircraft performance assumptions, and so forth) would be programmed into the FMS, and some of these data would be displayed on cockpit CRTs. Linkages, however, among the various flight control and display systems and electronic IAP charts have not been standardized as yet, thus, it is not known whether IAP data would be electronically transferrable to the Nav-Comm radios and associated displays, or might have to be manually entered if the flight plan stored in the FMS is altered.

Although cognitive demands on the pilot may be reduced by FMS automation, such systems today are difficult to reprogram if there are any changes in the flight plan, and changes in the initial flight plan are an everyday occurrence. Moreover, the more automated the avionics suite and the more functional capability it has (witness all of the current generation glass cockpit aircraft), the more demanding is the system operation. There may actually be too many system configuration alternatives. From a cockpit system design viewpoint, automation may simply trade off one kind of cognitive complexity (plan ahead and remember data) for another (plan ahead and remember how to access the data and/or make changes). The full nature of this trade-off is not yet known (Wiener, 1988).

4.8 Company Operations Policies

Each company that is involved in commercial aviation has standard operating procedures and policies that may or may not differ from those of another company. Policies and procedures are dictated by company philosophy, economics, and route structure. The equipment that air carriers select depends on their route structures, expected loads, revenues, and geography. Short haul operators can expect to spend a lot of time in traffic patterns, and long-haul operators spend a lot of time at cruise and comparatively little time in traffic patterns.

If FMS reprogramming is a problem, then one would expect such systems to be more attractive to long haul operators than short haul operators; thus the need for the IAP chart to provide backup information to a preprogrammed FMS might vary, but the fundamental information on the IAP probably is the same for these two example situations. What is different is the workload of the pilots over the entire duration of the flight; hence the design and configuration of an electronic IAP must carefully consider the cockpit activity throughout the flight, and must insure that the workload associated with electronic IAP manipulation does not add materially to an already high workload in the cockpit.

The logistics of updating electronic IAP data might vary from operator to operator as a function of how such a system is implemented. For example, one air carrier has said that if it has an ELS (with IAP data on it), the aircraft would request ELS data from a ground computer and the required data would be uplinked to the aircraft; pilots would have to check such data for accuracy and completeness. For other carriers, the data would be contained on each aircraft; in this case when the last update was made for any given procedure would become an important element of information for the pilot to verify at the beginning of a flight.

Regardless of source, the validity and completeness of the IAP data, along with the airport and runway identifiers (an indication that the displayed chart is the latest available update) become important parameters for pilots to remember and check prior to each use.

4.9 Maintenance Status

The needs for information and the way it is portrayed might vary with the maintenance status of the aircraft. Obviously, if there is an avionics electrical failure or the aircraft looses a primary power source or bus, full capability might not be possible. The IAP charts must portray information needed in such degraded cases, perhaps alternate approaches and redundant facilities. If fuel is low, it might be useful to know the locations of nearby airports. If an engine has been lost, obstacles and minimum terrain clearance altitudes could become more important than when operations are more normal.

4.10 Aircraft Performance Characteristics

Aircraft performance characteristics play a role in the use of IAPs. In general, as aircraft speed increases, it takes longer and requires a larger radius to turn, more space is required to descend, and less time is available to traverse a given distance; this requires the pilot to plan the flight further and further "ahead" of the aircraft. The more complex the aircraft, the more things have to be done prior to descent, and prior to landing during descent.

Even in low performance aircraft, pilots tend to plan well ahead of the aircraft; for example, most pilots study expected approach plates during low workload cruise segments, and plan how they are going to execute the descent and approach, how they are going to sequence the Navigation and Communication radios, and what facilities they are going to use to cross-check the validity of navigation data. So if STARS, approach charts, and SIDS are to be automatically sequenced, there will be a need for look ahead and browse features for pilots to plan descents and approaches to stay well ahead of the aircraft.

4.11 Geography, Topography, Culture

Surrounding terrain makes a difference in what a pilot pays attention to and how he or she operates the aircraft. High terrain is important to the pilot in mountainous country, and obstacles are important when being radar vectored. Controllers have vectored aircraft into mountains (in Los Angeles). Terrain and obstruction clearance is assured only within short lateral distances from the charged course (track) centerline. Published minimum en route altitudes are not always the same as minimum vectoring altitudes (not shown on navigation charts) or minimum obstacle clearance altitudes. Therefore, terrain and obstacle clearance becomes even more important when pilots are radar vectored.

Both topography (mountains, lakes, and so forth) and cultural features can be of value in orienting the pilot and generating expectations of what will be seen when breaking out of the clouds or nearing the ground in a low visibility approach. For example, the edges of a city could tell the pilot where to start expecting city lights. Approach light configurations and airport building, runway, and taxiway layouts are obviously important, especially when there are multiple runways in the same direction, or multiple airports nearby with similar runway directions.

Aberrations do occur. For example, at Orlando Herdon (Executive) airport, the East-West tollway lights are easily mistaken for runway lights at night and in low visibility. The illusion is so compelling that the approach plate has a warning about it. Another documented illusion is that of being too high if the runway is on an up-slope, and being too low if the runway is on the down-slope. Also, black holes caused by dark bodies of water on the approach end of the runway have been demonstrated to cause vertical flight path illusions. Where necessary, approach plates should mention such perceptual phenomena.

5. INFORMATION REQUIREMENTS OF THE INSTRUMENT APPROACH TASK

Current IAP charts are so cluttered with information that it is necessary to determine if all of the information currently provided is required for the task. A determination of the importance and frequency of use of the information displayed on charts also will help in the design of future IAP charts. Several researchers (Blanchard, 1991; Boeing, 1991a; Boeing, 1991b; International Air Transport Association, 1975; Mykityshyn and Hansman, 1992, Ricks, Jonsson, and Rogers, 1993) have studied the information requirements of the IAP task. Insight into the information requirements of the task was also provided by cognitive task analysis.

A review of the literature on IAP information requirements indicates that the information required is highly dependent on the situation (Boeing, 1991a) and that pilots have a great deal of trouble identifying information items for removal from the charts (Blanchard, 1991). Ricks, Jonsson, and Rogers (1993) have shown that pilots acquire information from approach plates 42 percent more often in a non-precision approach than in a precision approach. He has also shown that 18 percent more information was acquired in vectored scenarios than non-vectored scenarios.

Because each of the researchers used different methods and different scenarios in determining information requirements, the results were varied. For example, since Mykityshyn and Hansman's (1992) study looked at information requirements through three phases of flight, the missed approach information was naturally most important in the missed approach phase. In contrast, Boeing used a scenario for their subjective analysis that did not incorporate a missed approach. Therefore, missed approach information was rated very low in importance. However, three conclusions can be drawn:

1. Pilots would prefer to continue to have all of the information currently displayed on IAP charts (with the possible exception of obstacles). Although they may not use all of the information for every approach, there are situations in which they would like to have all of it.

2. Pilots' information needs change throughout the approach task.

3. There is evidence from different experiments to indicate that there may be some core group of information items which can be identified as most important in the instrument approach task (Hofer, 1993).

The information gained through the cognitive task analysis provides some explanation and elaboration of these conclusions. Most importantly, the cognitive task analysis revealed that the information on IAP charts is used in two distinctly different ways:

1. The IAP chart is used as a reference which provides specific pieces of information which are read off the chart and used immediately. For example, a pilot will read a communication frequency off the chart and then immediately tune the radio to that frequency. The same is true of NAVAID frequencies. Pilots also may use MDAs in the same way--read the altitude and then set a bug (marker) on the altimeter for that altitude.

2. The IAP chart also is used for planning purposes. During the descent or preapproach phase, the pilot will review the chart and plan the approach. The pilot will look at all of the NAVAIDs available for the approach to decide which NAVAID frequency to tune into which receiver so that in the end the primary (or possibly some other) NAVAID is tuned into the number one receiver. The pilot may decide to tune another NAVAID as a double check for the primary. The pilot also will look at terrain information (if the area is unfamiliar) to construct a mental picture of the terrain surrounding the airport, especially in the missed approach area. The pilot will look at the airport layout and runway light configurations to form a mental picture of what to look for as the approach is made.

The second manner of using IAP charts sheds some light on the above conclusion that pilots do not want to give up any of the current information provided on IAP charts. Although they may not use all of the data specifically to perform some action, they do use it to help plan ahead and to develop some expectations for the approach. The value of this information is not easily measured; however, cognitive psychologists know that having the correct expectations can make a large difference in performance of perceptual tasks.

The task analysis also reveals the way in which pilot information requirements change throughout the approach. Most of the information on the approach chart is used during the descent or preapproach phase. Certainly the information that is used for planning purposes is used during this time. The pilot also will make the initial communication and NAVAID frequency settings at this time. Later in the approach (most likely during the initial approach phase) the pilot may refer to the approach plate to change these settings or to double-check them. During the final approach phase and at the very start of a missed approach, the pilot is usually too busy to refer to the approach plate at all.

Finally, an initial attempt to identify the core group of information is presented in the following Table 1. These items come from at least one of the following sources:

1. The top 36 (category A) of Boeing's (1991) list of "primary items" (with some editing and grouping since those items were so specific)

2. The top ten of any of Mykityshyn and Hansman's (1992) three phases of flight "most critical" items (again with some editing and grouping; there were also a number of overlaps for each phase)

3. The items determined to be important enough to be present in Huntley's (1993) "briefing strip" for improved paper IAP charts

4. The top ten "most important" items selected by 20 percent or more of the pilots in a study by Blanchard (1991)

5. The items regarded as "most important" by one of the general aviation pilots interviewed for this report.

No specific method was used to determine where to cut off the list of items and the items are not listed in any particular order.

Table A-1. Information requirements for the IAP task

Information Item	References (1-5 from above list)
Primary NAVAID Information (especially frequency)	1-5
Approach or Inbound Course	1-5
Minimum Descent Altitude (DH for precision approach)	1-5
Minimums (Altitude and Visibility for the given aircraft category)	1-5
Communication Frequencies (ATIS, Approach, Tower, and Ground - with Ground the least important)	1-5
Secondary NAVAID Information (frequency most important)	1-5
Approach (Type of Approach to What Runway)	1, 5
Airport and City	2, 5
Missed Approach Point	1, 2, 4, 5
Missed Approach Instructions (Especially the first two actions)	1, 2, 3, 5
Final Approach Fix	1, 2, 4
Initial Approach Fix	1, 2, 4
Final Approach Course, Radials	1, 2, 4
Stepdown altitudes (or glide slope intercept altitude)	2, 3, 4, 5
Airport diagram (especially runway specifics, runway light configuration)	2, 3, 4
Minimum Sector Altitudes	2
Touchdown zone (or airport) elevation	1, 3
Notes	3
Distances/DME or Time to Missed Approach Point	1, 4, 5

6. COGNITIVE IMPLICATIONS OF THE APPROACH TASK

The instrument approach task is quite complex. There are a number of different cognitive skills required of the pilot. These skills include, but are not limited to, the following:

- The pilot is subject to high temporal demand. Perception of workload, problem solving, and decision making performance are all highly dependent on time.

- The pilot must have a great deal of background knowledge. This includes knowledge of navigation systems and IFR rules (including a number of specific conditional rules for the instrument approach).

- The pilot must remember to perform different sequences of actions at different phases of the approach. The pilot may or may not have memory aids for each of these actions. If a pilot forgets to perform any one of a number of actions during the approach, the workload later will increase, greatly increasing the difficulty of the task.

- The pilot must be able to quickly and accurately extract needed information from various sources (ATIS, ATC, IAP chart, co-pilot, or aircraft displays) and remember the information long enough to apply it (turn to the appropriate IAP chart, enter in a frequency, set a timer, etc.).

- The pilot must be able to review and integrate the information on the approach chart to help in planning the approach and setting up expectations for the approach.

- The pilot is constantly subject to interruptions such as ATC communication which may affect memory of actions to complete and of information to apply.

- The pilot is constantly subject to ATC requiring changes to the planned approach.

- The actions that a pilot must perform will be highly dependent on a number of situational factors, therefore, the pilot must be able to "tailor" his or her procedures to each approach.

- The pilot's need for information is highest during the preapproach phase. Workload is highest from the initial approach phase through landing. During the final approach, the pilot must focus on flying the aircraft and can not contribute cognitive resources to other tasks.

- The pilot must continually monitor the flight of the aircraft during the approach.

- The pilot must remain aware the aircraft position/location throughout the approach.

- The pilot may be required to perform mental arithmetic to determine proper headings, accounting for wind.

- The pilot must use spatial abilities to rotate information on the IAP chart to match it to the aircraft's current orientation.

- The pilot uses a number of "rules of thumb" to aid in performance of various tasks.

- The instrument approach task is a stressful situation for the pilot. Stress can cause decreases in cognitive ability and can lead to cognitive capture or tunneling. Stress may cause the pilot to focus on one part of the task to the exclusion of other important parts of the task.

7. DESIGN GOALS FOR INSTRUMENT APPROACH PROCEDURE CHARTS

Cognitive principles can be applied directly to each of the skills presented above to provide recommendations to help the pilot in performing his or her task. A cognitive handbook for the design of IAP charts should provide concrete guidelines to help designers follow these recommendations:

- Make information quickly accessible.
- Reduce the amount of background knowledge that is required for the task.
- Reduce requirements for memorization of rules, actions, symbols, procedures.
- Provide an organization or structure for the task.
- Display information in a manner that will help the pilot or crew to both plan the approach and be prepared for future segments of the approach.
- Provide memory aids.
- Provide a method to highlight information that is "currently being used" (held in short-term memory while it is being applied). This will help the pilot relocate it quickly if necessary.
- If possible, account for situational factors automatically.
- Make information required during the initial approach phase easy to locate and read.
- Provide a method for advance highlighting of information required during final approach, or present it in a manner that is easily kept in memory.
- Limit functions and keep them simple.
- Do not add any extra steps or workload to the task.
- Display information to help the pilot remain aware of his or her aircraft's current position.
- Take advantage of common (and efficient) rules of thumb.
- Make information from different sources (ATIS, ATC, IAP charts, Instrument displays) consistent in terms of terminology and symbols.

8. THE CURRENT DESIGN OF IAP CHARTS

The current design of IAP charts is in the form of a 5" X 8" paper chart produced by either the National Ocean Service (NOS) or Jeppesen. NOS charts are available in "booklets" based on regions. Jeppesen charts come in separate pages to be placed in a notebook--this provides Jeppesen users with the ability to update their charts more frequently and at less cost than if they had to replace whole regions of charts. NOS charts are less expensive than Jeppesen charts. However Jeppesen charts are used by more than 90 percent of U.S. commercial airlines (Mykityshyn and Hansman, 1992). Both chart makers divide their charts into the following meaningful areas:

8.1 Headings

Margin identifications or headings include information such as the name and location of the airport and the procedure number of the chart. Jeppesen also provides communication frequencies for the airport and minimum safe altitudes in the "Heading" section at the top of the chart.

8.2 Plan-View

The plan-view provides a bird's eye view of the airport and surrounding area, and the procedure. Information in this section of the chart includes the initial approach segment, procedure turn, final approach segment and instructions, en route facilities, feeder facilities, terminal routes, holding patterns, waypoints-with-data, radio aids to navigation, obstacles, spot elevations, and many other important pieces of information required for an instrument approach. Much of this information is displayed in symbolic form with a legend provided on a different page. Unfortunately, many of the symbols are different for the two types of charts.

8.3 Profile View

The profile view is a side view of the approach, providing a graphical depiction of altitude information. The profile view depicts the minimum altitude for procedure turn, minimum distance for procedure turn, altitudes over prescribed fixes, and distance between fixes. Also near the profile view (within it to the top left or right for NOS charts) and immediately below it for Jeppesen charts are the missed approach instructions. Missed approach instructions are written out in text (smaller type is used on the NOS chart than on the Jeppesen chart).

8.4 Aerodrome Sketch

NOS charts provide an Aerodrome sketch directly on the IAP chart. It includes information such as airport elevation, usable runway length, approach lights, runway gradient, time and speed table from final approach fix to missed approach point, and more. Jeppesen places the aerodrome sketch on the back of the first instrument approach procedure for a given airport. This allows them to provide the information on a much larger scale and to provide even more information. However, displaying information on a separate page creates the added tasks of finding the page, finding a place to display it, and flipping back and forth between the aerodrome sketch and the IAP. Clearly there are advantages and disadvantages to both methods.

8.5 Minimums

The final major section on current IAP charts is the minimums section. Both chart makers place this information at the bottom of the chart. This section contains important information about minimums for the approach such as decision height or minimum descent altitude, and visibility. Jeppesen charts provide minimums on the IAP chart for special "instrument out" conditions while NOS charts provide adjustments to determine these minimums on a separate page. The same advantages and disadvantages that apply to the aerodrome sketch apply here. However, because Jeppesen charts do place the aerodrome sketch elsewhere, they are able to display more minimum information than NOS in the same size type.

Standard Terminal Arrival Route (STAR) charts and Standard Instrument Departure (SID) charts are also available from both Jeppesen and NOS. Jeppesen files these charts with the airport's approach charts. NOS files SIDs with the airport's approach charts; however, they provide STARS at the front of each NOS booklet. The purpose of STARs is to provide a standard method for departing from the en route structure and navigating to the pilot's destination. SIDs have a similar function for providing a transition from the airport to the en route structure.

NOS and Jeppesen STARs and SIDs are currently designed with three major sections. The margins are very similar to the margins for IAP charts. The plan view is also similar to that for IAP charts. The plan view may be oriented vertically or horizontally depending on the layout of the route. The plan view contains navigation and communication frequencies at the top left or right of the chart. The symbols on the plan view are similar to those for the IAP charts. A legend for these symbols is provided on another page. The plan view is likely to portray departure and arrival routes, terminal routes, holding patterns, waypoints-with-data, radio aids to navigation, reporting points/fixes, special use airspace, and nearby airports. The final section of STARs and SIDs is the text box. The text box contains a textual description of the arrival and departure and may include a description of one or more transitions to the departure or arrival.

9. COGNITIVE ISSUES IN THE DESIGN OF IAP CHARTS

The design goals delineated by the task analysis and the review of current IAP charts indicate problems and cognitive issues with the current design of IAP charts. Many of these issues are due to the limits imposed by a five by nine inch paper chart. The following section presents these cognitive issues, potential solutions to problems, and also presents solutions that may be available through the use of electronic IAP charts.

9.1 Perceptual Clutter

Clutter is the most often noted problem with the current design of IAP charts. Unfortunately, clutter is a difficult concept to define and is even more difficult to quantify. Perceptual clutter--clutter created by the density of the information of the display and the discriminability of that information--is a problem any time a large amount of information must be displayed in a small amount of space. Perceptual clutter increases the time required for a pilot to locate and extract needed information. There are two ways of reducing perceptual clutter on a display: (1) decrease the density of information on the display or (2) increase the discriminability of information on the display.

Decreasing the density of information on a display can be achieved either by reducing the amount of information on the display or by increasing the display area. Reducing the amount of information on the display is accomplished by removing any item that is considered irrelevant for the task. The dynamic nature of electronic displays of IAP charts provide an opportunity to customize charts and eliminate extraneous information. For example, a pilot may be able to choose or preprogram which of the routes he or she will be following; the electronic chart could then display only that route and the NAVAIDs required for it. The pilot also may enter the aircraft category (or even better, it could be determined automatically) and only the information for that aircraft category would be displayed.

Increasing the display area may or may not be possible with electronic charts. Paper charts are 9" x 5" because this is a standard size and easy to handle. Using more than one page for paper charts is not desirable because of the increased storage problems, printing costs, and handling problems. The size of electronic charts also will be limited due to the availability of cockpit "real-estate." In addition, the resolution of electronic displays requires that symbols and text be larger than on paper, thus increasing the density of information on the display. Electronic IAP charts may provide information on separate pages, but the method of switching displays will have to be carefully evaluated.

As for the second method of reducing perceptual clutter; an increase in the discriminability of the display can be achieved in a number of different ways. The proper use of white space and the proper location of text and symbols can increase the discriminability of a display. Providing text and symbols which are visually distinctive also can increase discriminability. Both of these methods will be discussed in the section on text and symbols. Another method for increasing the discriminability of a display is through the judicious use of coding and highlighting.

Schultz, Nichols, and Curran (1985) researched decluttering of a graphic display by removing or minimizing information of lesser importance and found that removing text and making less important symbols smaller was as effective a decluttering technique (in terms of search time for the important items) as was complete removal of the less important items. This has interesting implications for the approach task since there may be reasons to show symbols for NAVAIDs which are not planned to be used (so that pilots may see the other options that are available if necessary), but it may not be necessary to display all of the information associated with them unless it is specifically requested. Schultz et al. (1985) concluded that ". . . the effectiveness of decluttering methods depends upon the degree to which each method makes essential graphic information distinctive from nonessential information."

9.2 Cognitive Clutter

Unfortunately, eliminating perceptual clutter does not necessarily eliminate all of the clutter associated with the display. Clutter associated with determining the relevancy of the information on the display to the task at hand can be can be referred to as cognitive clutter. A display that provides information that is perceptually discriminable may still be subject to cognitive clutter in the display if the perceived object must be processed deeply to determine its meaning and therefore relevancy. Cognitive clutter refers to the complexity or confusability associated with the meaning of objects represented on the display. For example, if an individual is shown a symbol and asked to locate that symbol on the display, the time that it would take to locate the symbol may be a indication of the display's perceptual clutter. If, however, the individual is asked to locate the primary NAVAID frequency on the display, the search time may be indicative of both the perceptual and cognitive clutter on the display. Implicit information required for the task may interfere with the explicit information on the chart in a way that induces cognitive clutter. The nature of the task becomes important in considerations of cognitive clutter.

Methods of reducing cognitive clutter include reducing perceptual clutter (since this usually reduces the total amount of information to be processed), providing information that can be perceived directly without a great deal of information processing, grouping information in a meaningful way, and organizing information in a manner which is meaningful to the task. Each of these methods is discussed in more detail in the following sections.

9.3 Organization and Grouping of Information

The proper organization and grouping of information is essential to a display of instrument approach information. Organization and grouping can be used to reduce both perceptual and cognitive clutter and also may aid the pilot in planning and executing the approach. Current methods consistently delineating plan view, profile view, and minimums provide some organization for the task. The plan view allows the pilot to form an overall picture for the entire approach and may help in the task of planning the approach. The profile view helps the pilot to visualize the vertical navigation through the approach.

The problem with the current organization is that it does not facilitate fast retrieval of specific information items. To locate a NAVAID frequency, a pilot must first identify the aircraft's current position within the plan view, then locate the NAVAID, and then locate the frequency. This requires the pilot to visually step through the plan he or she may have already created earlier in the approach. Huntley (1993) recognized this deficiency with paper charts and incorporated a "briefing strip" which contains the information that must be accessed most quickly and most often. This allows the pilot to use the entire chart for planning, but to obtain specific information the pilot need only refer to the top line to quickly read the information.

Consistency is an important principle in the organization of information on displays. If the information a pilot wants is always in the same place, the pilot will know immediately where to look for it. Mangold, Eldredge, and Lauber (1992) state that eye movement patterns are influenced by pre-existing knowledge of how charts are organized. In the current implementation of the plan view, the information is located spatially with the result that it is not located consistently. Huntley's (1993) design allows for location of important information both spatially and consistently. Consistent location of information is especially important when the pilot can only take a single glance at the display. The effects of pilot expectation are especially powerful in this situation (Neisser, 1976).

Electronic charts have the potential to greatly facilitate the instrument approach task by providing separate displays for planning (with a spatial orientation) and for execution. The display for execution would contain only specific information identified during planning as necessary and would display the information in a consistent location and with very little perceptual clutter. Research by Stokes and Wickens (1988) has shown that spatial maps are better for planning while route lists are best for navigation.

Another basic principle in the design of displays is that related information or information that must be processed together should be grouped together. One way of grouping information is by locating the information close together in space. Another method of grouping information is through the use of coding. A method of grouping that may become more prevalent with electronic displays is through layering on screens. Mykityshyn and Hansman (1992) studied pilots' use of a prototype EIAP with a decluttering mechanism which allowed maintenance or suppression of layers of information. The layering or grouping of information was broken into 6 categories--primary approach information, secondary NAVAIDS, terrain information, minimums, missed approach information, and procedure turn information.

Neisser (1976) also has done research on grouping and clutter. He found that, using a visual task similar to a selective listening shadow task, people can easily attend one visual stimulus (a video game) when another is superimposed over it (as easily as without the superimposed game). Performance deteriorates when they have to attend to both at the same time. "Only the attended episode is involved in the cycle of anticipations, explorations, and information pickup; therefore, only it is seen" (Neisser, 1976). This suggests that, with the appropriate cues (in this case the motion of the games), individuals have the ability to do some of their own "decluttering." However, Neisser's participants were not subjected to the same environmental conditions as instrument approach pilots.

9.4 Direct Perception and Integration of Information

One of the most basic cognitive principles in the design of displays is to display information so that it can be directly perceived. The meaning of the information should be immediately obvious and should not require a number of mental transformations of the information. Unfortunately, the nature of the IAP task is not very direct. According to Ritchie (1988), pilots must depart from the conceptual framework of the primary task and "think in electronics." The cognitive task analysis reveals that the pilot must integrate information from a number of different sources. Much of the information, such as radio frequencies, has no inherent meaning in flying, geography, or navigation (Ritchie, 1988).

If the IAP chart can do some of the integration of the information for the pilot so that information can be directly perceived, the instrument approach task could be made easier. There are many different ways of achieving this integration. First, symbols should look like the objects they represent. Huntley (1993) has demonstrated this principle in his improved paper IAP chart by removing the runway light acronyms and replacing them with a symbol that shows the runway light configuration the pilot expects to see. The pilot no longer has to decipher the acronym and then remember what that lighting system looks like in order to prepare for landing. The proper use of population stereotypes also facilitates direct perception of information.

Electronic displays provide the opportunity to do even more information integration for the pilot. For example, the electronic chart could automatically detect the aircraft's speed, calculate the time to the missed approach point, and display it as a countdown clock (that could be automatically updated as the aircraft speed changes). Currently the pilot has to estimate his average speed, interpolate from a table of speeds and times to get the correct time, and then monitor his timer.

Possibly the most helpful information integration that an electronic chart may be able to provide is the display of the aircraft's current location. O'Hare and Roscoe (1990) state that map displays that show the position of the aircraft yield improvements in a pilot's ability to maintain geographic orientation, plan complex routes, and control position. Mykityshyn and Hansman (1992) tested a system which displayed real-time aircraft location and every pilot commented that the real-time aircraft position depicted by an aircraft symbol provided a cue for error reduction.

An electronic IAP chart also could make perception of information more direct by presenting a track-up or ego-centered reference frame for the pilot. This reduces the requirements for the pilot to perform spatial rotation of information to his or her reference frame. However, as there are a number of other contributing factors involved with a display of this type, it is discussed in more detail below.

9.5 North-Up (Static) vs. Track-Up (Dynamic)

An electronic map display offers the option of orienting the map in the same direction as the aircraft (track-up). Pilots are mixed in terms of preference for a static north-up map or a dynamic track-up map. Mykityshyn and Hansman (1992) showed that, after having an opportunity to use both types of maps in a simulated approach, pilots preferred a static map which showed the location of the plane dynamically over a dynamic map which changed orientation based on the location of the plane.

Researchers are also mixed on their opinion of which display method is better. Roscoe (1980) states that track-up displays are generally better than north-up displays but are subject to more control reversal errors. Harwood (1989) states that north-up displays are better for a greater variety of tasks but track-up displays are better if one is lost. Aretz (1991) states that north-up is better when the task requires a world reference frame (survey knowledge), and that track-up is better when the task requires an ego-centered reference frame (route knowledge).

Based on the cognitive task analysis, the instrument approach task requires survey knowledge during the planning part of the task, and route knowledge during the execution of the task. This would indicate that a north-up map showing real-time aircraft position would be best for planning of the task (as was preferred by pilots). During actual execution of the task, either a route list (an ordered list of specific information), or a track-up display would be recommended.

Other display options are also available. A "visual momentum" technique has been proposed by Aretz (1992) which provides a wedge on a north-up map that indicates the area which is within the pilot's ego-centered view. Roscoe (1980) suggests the use of a "frequency separated" display. This display shows the conventional moving horizon in conjunction with an indication of roll rate and acceleration with the aircraft symbol. Both researchers have had positive results with studies of these integrated techniques.

9.6 Terrain Information

Terrain information is depicted in the plan view in the form of spot elevations and significant obstacles. There is no requirement to depict all elevations or obstacles, so this information adds clutter to the display without providing very meaningful information since pilots are told they can not rely on this information (Jeppesen Sanderson, 1988). Friend (1988) complains that the presence of spot elevations and obstacles may lead pilots into believing the obstacles shown are the only obstacles in the approach area. Pilots often suggest that the display of terrain information be changed. Unfortunately, opinions are mixed on how the change should take place. Many pilots suggest that terrain information should be removed altogether with only Minimum Sector Altitude needed for instrument approaches (Mykityshyn and Hansman, 1992). Others would like to see terrain information increased by providing contour lines to display terrain (Friend, 1988).

According to Kuchar and Hansman (1992), IAP charts provide the primary terrain information for terminal area operation. In contrast, Blanchard (1991) states that "The IAPC is not detailed enough/nor designed for use in obstruction avoidance. . . ." There may be a lack of terrain information available in the terminal area but there is still some question as to whether or not the IAP chart is the appropriate place to display terrain. Kuchar and Hansman (1992) tested terrain situation awareness by issuing to simulator pilots erroneous vectors into terrain. Pilots avoided hazards only 3 of 52 times with current terrain depiction methods. After pilots were given responsibility for terrain avoidance, they recognized terrain hazard 50 percent of the time with a spot elevation display, and 78 percent of the time with contour display. One significant problem that has been demonstrated by this research is that pilots do not double-check ATC vectors, no matter how the terrain information is displayed. Because pilots are already loaded with tasks during an instrument approach, it is easier for them to simply take the information given to them by ATC. Unless terrain is displayed in a manner that makes it simple for them to double-check ATC vectors, or they have some reason to doubt the information from ATC, they probably will not check.

Electronic displays have advantages and disadvantages for terrain display. The quality of electronic displays is inferior to that of paper displays in terms of shading and other methods of displaying terrain contours. However, it is less expensive to use color on electronic displays than on paper so that color may make a viable option for the display of terrain information. In addition, there is the possibility of providing a "terrain layer" that is available at the push of a button. Electronic displays may also be able to provide terrain information only in the area immediately surrounding the aircraft's position or only when the aircraft is within a certain distance of terrain (possibly linked to some type of collision avoidance system).

9.7 Text and Symbols

Another commonly mentioned problem with current IAP charts is the size of the text and symbols. They are so small that it takes close inspection to perceive and understand them. Perception of information is a combination of bottom-up processing--detailed analysis of stimulus information--and top-down processing--an analysis of the holistic properties of the stimulus using context and expectations. When stimuli are very small, bottom-up processing is required. Unfortunately, when viewing conditions are poor, people are required to use more top-down processing (Eysenck, 1984). The use of electronic displays will require that both symbols and text be made larger.

There is also a problem with the sheer number of symbols. Pilots must memorize the most common symbols and then refer to a legend for other symbols. One method of overcoming this problem is to provide symbols which directly convey the meaning of the object they represent. Unfortunately, in the case of IAP information, this is not always easy. Standardization of symbols across other displays also would help with this problem since well known symbols are processed more quickly than unfamiliar symbols. Electronic displays may make it even more difficult to design representative symbols due to resolution problems. However electronic displays also may provide quicker access to legends or definitions of the object presented. For example, electronic displays have the capability of allowing the pilot to select the object, then present information about that object for a short period of time.

The location of text and symbols on the chart is also a concern. Other text or symbols close to a word prolong the time that it takes to recognize the word, especially if the information is located near the beginning of the word (Noyes, 1980). In current presentation, frequencies and identifiers run together with no distinctive separation, making it more difficult to distinguish them. Displaying identifiers in smaller text may help in distinguishing the two separate words and may help promote top-down processing of the information.

In some cases there may be uncertainty about whether to use text or symbols. Pictorial representations are less disrupted by degraded viewing conditions, may take up less space than text, and in many cases can be perceived at least as quickly as text (Ells and Dewar, 1978). Osborne (1992) found that iconic missed approach instructions were comprehended more quickly and as accurately as instructions coded in text and that pilots indicated a strong preference for using icons in single pilot IFR conditions. However, one must be careful not to always choose a symbolic representation over text. If the object or meaning can not be represented directly by a symbol and is represented by an arbitrary symbol it will add to the pilot's memory load. Any introduction of new symbols should be evaluated for its effect on the entire task.

9.8 Coding, Highlighting, and Color

There are several methods of coding information that may help reduce clutter and facilitate quick recognition of information. Shape coding through the use of symbols is already in use on paper IAP charts. Size coding may be used to emphasize information of greater importance by displaying it in a larger size. Electronic displays provide designers with the opportunity to use other methods of coding such as highlighting (or bolding) and color.

Highlighting as a method of coding should be used sparingly since it may slow down a pilot's ability to retrieve unhighlighted material. Novel, unexpected stimuli are best used for warnings or cautions since they both draw attention to themselves and are well remembered (Eysenck, 1984). Color, on the other hand, may have the ability to provide a benefit in terms of speed of retrieval without any drawback (Martin, 1992). The pilots in Mykityshyn and Hansman's (1992) study found that color had a decluttering effect. It allowed them to "mentally eliminate" information of less interest.

The usefulness of color increases with increasing information density and complexity (Taylor, 1985) making it potentially beneficial for use on electronic IAP charts. Color has been successfully used on cartographic displays for helicopter Nap of the Earth navigation (Rogers, 1993). The use of color should coincide with population stereotypes so it matches the existing expectations of pilots.

9.9 Pilot Control

Many of these advantages of electronic displays require pilot control of displays or information to be displayed. If pilots are given the option to choose what and how much information is displayed, there is a potential that added workload related to memory of what is displayed, what can be displayed, how to display it, and the physical action required to display it, may in fact add to the difficulty of the task (Stokes and Wickens, 1988). Mykityshyn and Hansman (1992) tested a pilot selection decluttering mechanism and found that pilots who used the decluttering feature liked it. The pilots indicated that if they did not have time to use the feature, they wouldn't. Any electronic IAP chart that allows pilot selection of information should make that selection as easy as possible, keep the number of options to a minimum, and test the usability of the feature.

10. CONCEPTUAL GRAPH STRUCTURE METHOD AND RESULTS

As part of the cognitive task analysis of the instrument approach task. Gordon and Gill's (1993) cognitive task analysis was attempted. Gordon and Gill (1993) suggest a four-step process. In the first step, an initial interview is used to initiate a Conceptual Graph Structure (CGS) (Graesser and Gordon, 1991). This structure consists of source nodes, arcs, and terminal nodes. Nodes may be goals, goal/actions, events, states, styles, or concepts. Arcs are connections which may be reasons, means, "refers to," "is-a," etc. Structures which include goal hierarchy, taxonomic, spatial, and causal structures can be created using various source nodes, arcs, and terminal nodes. Gordon and Gill describe these structures and related terms in detail. After the initial CGS is developed, question probes are created based on the nodes within the CGS. Gordon and Gill also provide the question probes that should be used based on each type of node. The third step is to use the graph along with the probe questions to acquire further knowledge from experts. The final step involves adding the information acquired to the CGS. The method appears to be a very structured and thorough method of eliciting knowledge from experts.

All of the information from the literature review, pilot interviews, SME consultation, and simulator experience was used as input into the creation of a Conceptual Graph Structure. Figure A-1 is the initial attempt to create a CGS. Unfortunately, presentation of this CGS to SMEs revealed that the task had a number of contributing factors that caused the graph structure to be very complex and difficult to organize in any manner that could be easily followed.

Based on this result, it was determined that separate graph structures of the different types of approaches would be created, at a high level, focusing on referrals to the IAP charts. The first of these CGSs (for an ILS approach) is presented in Figure A-2. Further work to develop CGSs for other types of approaches may continue. However, the effort is very time consuming and detailed. The exercise did facilitate knowledge acquisition for the researchers but it seems that further work in this direction may yield diminishing returns. Even if further work on this method proves to be unsuccessful, the task description and cognitive implications presented in this report will continue to be examined through pilot interviews and jump seat rides.

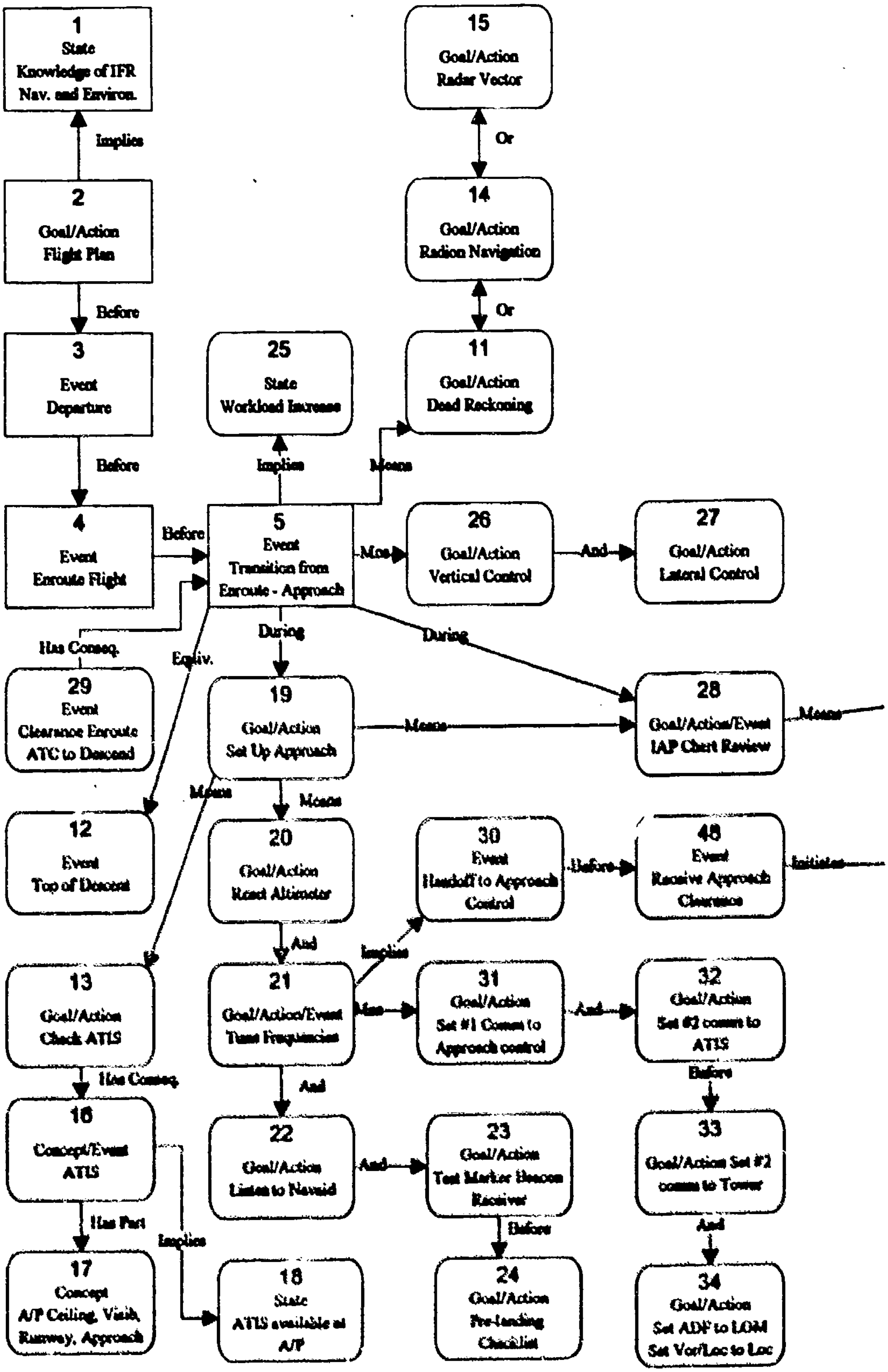

Figure A-1. Initial CGS of instrument approach task

Sample CGS. May be subject to methodological and technical inaccuracies.

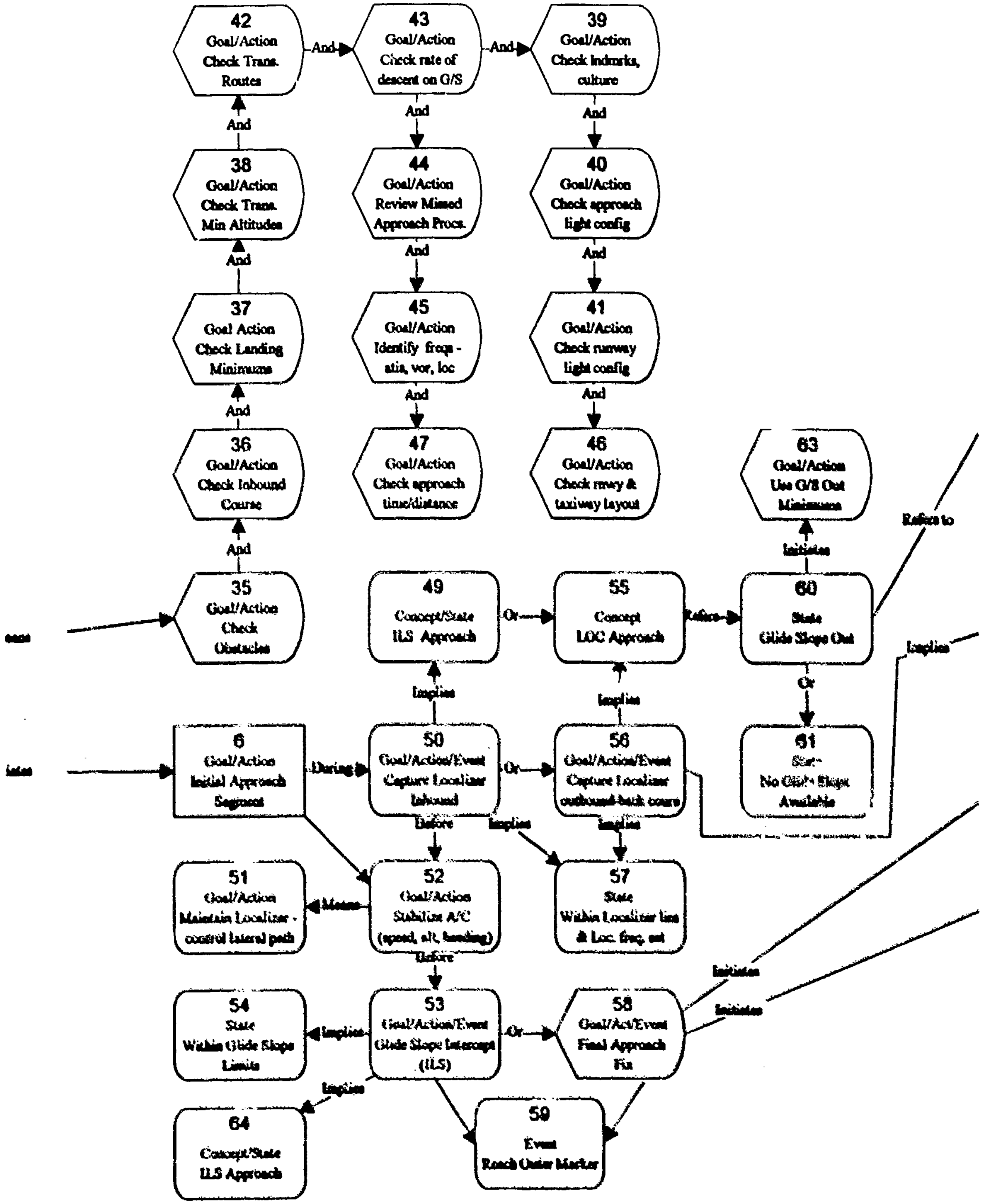

Figure A-1. Initial CGS of instrument approach task (continued)

Sample CGS. May be subject to methodological and technical innacuracies.

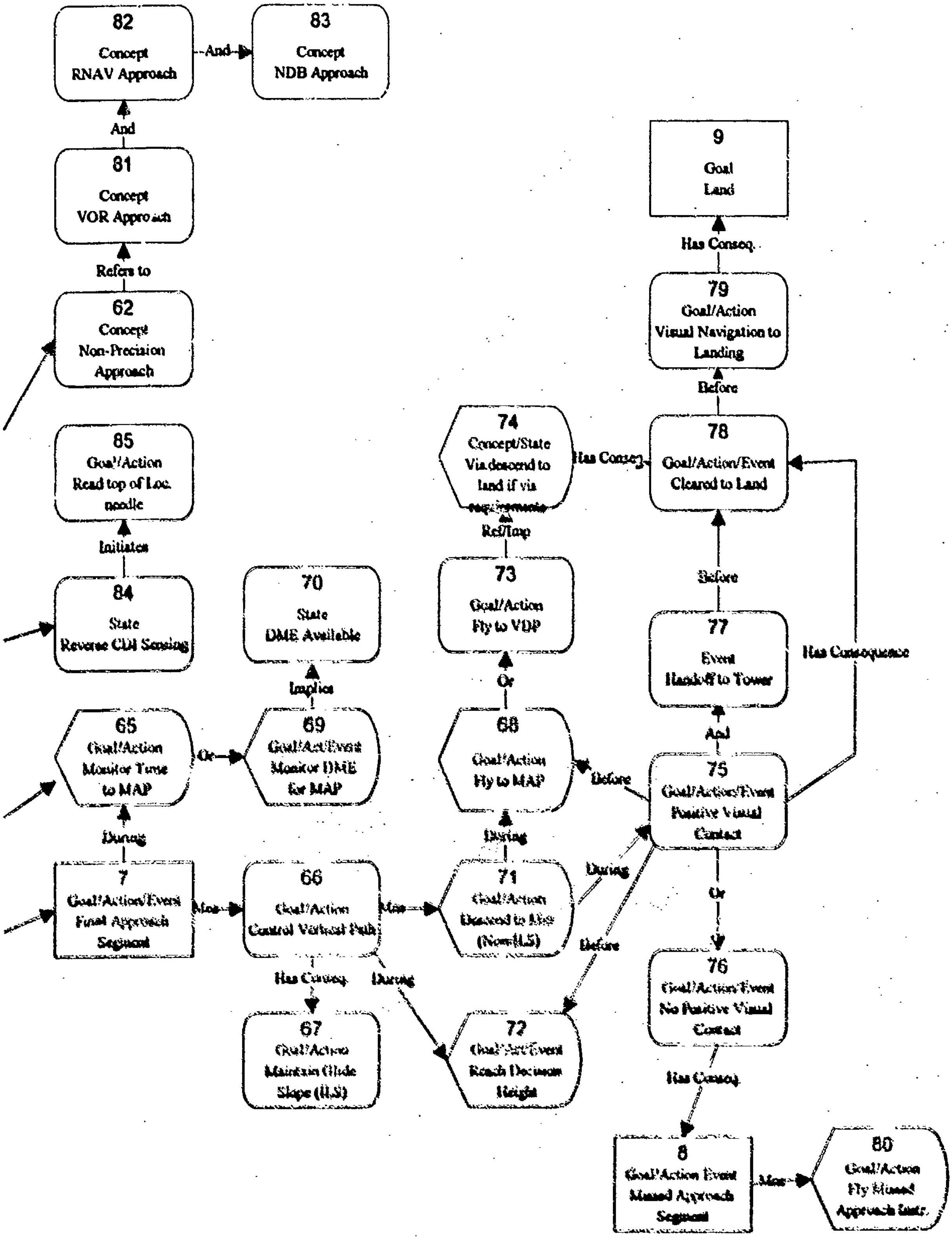

Figure A-1. Initial CGS of instrument approach task (continued)

Sample CGS. May be subject to methodological and technical innacuracies.

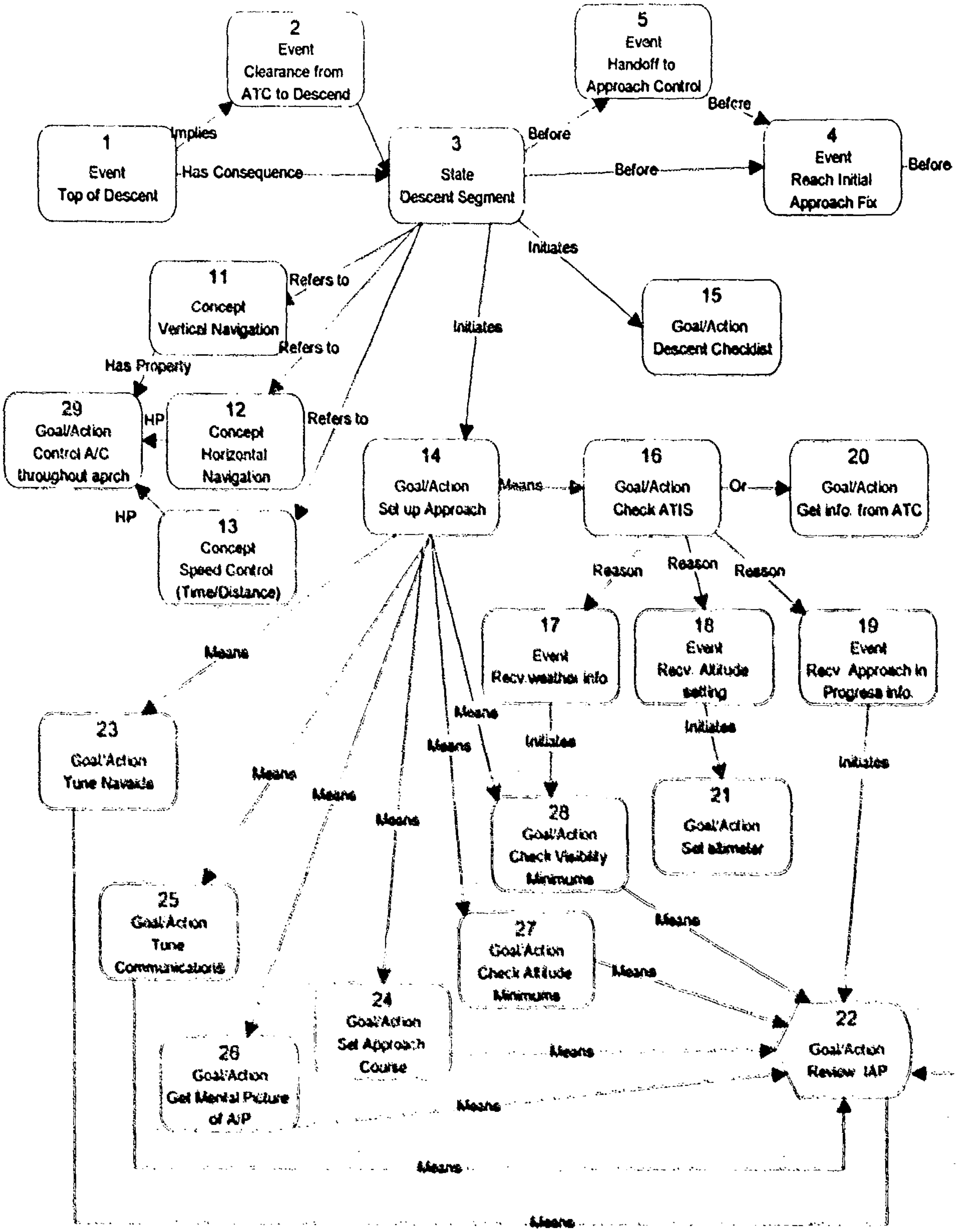

Figure A-2. CGS of ILS approach

Sample CGS. May be subject to methodological and technical inaccuracies.

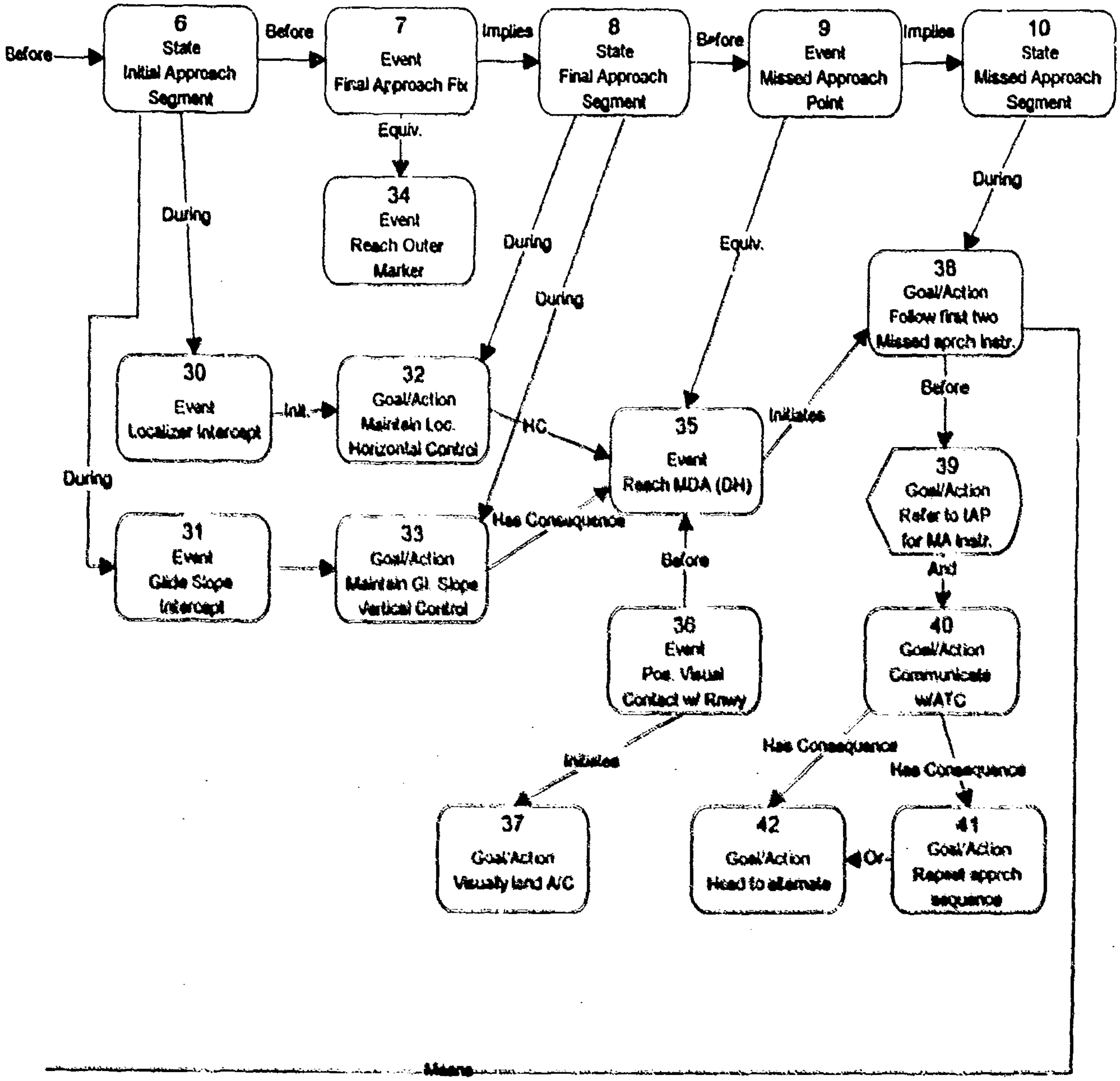

Figure A-2. CGS of ILS approach (continued)

Sample CGS. May be subject to methodological and technical inaccuracies.

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