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16. Abstract

The Advanced Automated En Route Air Traffic Control (AERA) Concepts research program exam the feasibility of applying a high level of automation to integrating aircraft separation assurance an traffic flow management into an air traffic management system for the year 2010 and beyond. As p this work, the program developed a new concept of human operations and procedures embodied in role of a traffic manager. This report presents hypotheses regarding the core operational and behav tasks of such a traffic manager. In addition, relevant psychological theories and frameworks are presented to provide a foundation for applying the associated psychological research paradigms. B on these presentations, an outline of areas requiring further research are presented, and a research approach for examining these areas is proposed.

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INTRODUCTION

1.1 BACKGROUND

Advanced Concepts for Automated En Route Air Traffic Control (AERA), a research and development program sponsored by the Federal Aviation Administration's (FAA's) Research and Development Service, examined the feasibility of applying a high level of automation to integrating aircraft separation assurance and traffic flow management into an air traffic management system for the year 2010 and beyond. As part of this work, a new concept of human operations and procedures was developed, which was embodied in the role of a traffic manager. The subsequent re-allocation of roles and responsibilities resulted in a proposed evolution of the human role from air traffic control to management of air traffic flows and of airspace resources. Advanced AERA Concepts described not simply an increase in the use of automation beyond that of AERA Services, but hypothesized significant qualitative changes in the basic human role in the air traffic management system of the future.

1.2 PURPOSE

The purpose of this report is to document a theoretical foundation upon which further research can be based that analyzes a human air traffic management role in a highly automated air traffic management system. The described role is sufficiently different from any of those in today's system that such research will be needed in order to establish human resource requirements for areas such as operational procedures, training, performance evaluation, and staff selection.

Hypotheses are presented regarding the core operational and behavioral tasks of such a traffic manager. In addition, relevant psychological theories and frameworks are presented to provide a foundation for applying the associated psychological research paradigms. Based on these presentations, an outline of areas requiring further research is presented, and a research approach for examining these areas is proposed.

1.3 AUDIENCE AND SCOPE

This report is aimed at two audiences: those interested in possible future human resource requirements for air traffic management, and those interested in human factors issues regarding the introduction of higher levels of automation in this field.

This report deals only with theories and implied research regarding the core air traffic management tasks of a theoretical traffic manager. Descriptions of the communication and coordination tasks of such a manager have not yet been developed.

1.4 CONTENTS AND ORGANIZATION

Section 2 presents the theoretical foundation and a narrative operational description of the core operations hypothesized for a traffic manager, summarizing the interaction of the manager with objects in their domain (such as displays).

Section 3 translates this description into an outline of specific task behaviors, specifying the kinds of actions being taken by the manager (such as *assessment, evaluation,* or *comparison*).

In section 4, hypotheses regarding the human cognitive processes underlying these actions and interactions are described. They provide a foundation for understanding the relevant human capacities in the proposed air traffic management environment, and for studying these capacities using relevant psychological research paradigms.

The theoretical descriptions presented in sections 2–4 provide a structure not only for detailing what is known, but complementarily, they indicate where further research is required to complete an understanding of a human role in air traffic management. Section 5 presents an annotated list of questions outlining these areas for further research.

Finally, section 6 presents a research approach for addressing the questions raised.

SECTION 2

THEORETICAL FOUNDATIONS AND AN OPERATIONAL DESCRIPTION OF A TRAFFIC MANAGER'S ROLE

The theoretical foundations and the operational description in this section have been presented with additional detail in previous publications. A narrative description of a traffic manager's role[1] in Advanced AERA Concepts is presented in *Advanced AERA Capabilities, a High Level Description* [1]. In addition, *An Evolution of the Human Role in the En Route Air Traffic Management System* [2] provides further details regarding the the current concepts of the human-computer interface and includes a detailed description of the theoretical principles that guided the development of the Airspace Manager's role.

2.1 THEORETICAL FOUNDATIONS

The theoretical foundations presented in this section shaped the development of the description of the traffic manager's role in 2.3. The first three subsections present design principles regarding the role of the human in any highly automated control system. The fourth subsection presents a theoretical perspective on the nature of managing air traffic.

2.1.1 Holistic System Design

The principle of holistic system design postulates that task allocation to the human and the automation should be based on overall system performance rather than the performance of any individual task. Central to this principle is that to maintain overall efficiency, the tasks allocated to the human need to be coherent, and performed on a regular basis at an appropriate level of complexity.

The reason for emphasizing this principle is that, in the past, attempts to incorporate automation into existing systems were often piecemeal; the human's tasks were gradually turned over to the automation as computers became more sophisticated. The human tasks that remained were often incoherent, and performed on an irregular basis at a high level of complexity. It has been found that roles such as these result in low job satisfaction, low self-confidence, high tension, a sense of futility [6], and consequently relatively low system performance.

Hypothetically, some tasks allocated to the traffic manager could be performed by the automation in many instances, but would require human intervention in others. With respect to the holistic design principle, this type of task may need to be performed by the

[1] This is the role of the Airspace Manager in Advanced AERA Concepts.

human on a regular basis instead of on such an occasional basis depending on the task environment. An example of the application of this holistic principal is illustrated in figure 1. The left-hand graph illustrates a task allocation where the automation might be able to plan an air traffic management strategy to resolve some complex airspace situations, but the complexity of other situations may be beyond its planning ability and require human intervention. In the hypothetical task environment illustrated, the irregularity of the human involvement in planning reduces the human's situational awareness and consequently the overall system efficiency. In such a task environment, the human should be allocated a role in all strategy planning instances, thereby improving situational awareness and consequently overall system efficiency. This is illustrated in the right-hand graph in figure 1. The automation's role in strategy planning should then be to provide support for the human manager.

2.1.2 Minimize the Consequences of Human Error

This principle postulates that to take full advantage of human abilities, interactive systems should not be designed to eliminate human error, but instead to minimize the consequences of human error in order to maintain safety and overall system efficiency. According to Rouse [7], eliminating human error using proceduralization, interlocks, and other means, would probably also inhibit human innovation. Instead the system should be designed to facilitate the innovation, adaptability, and flexibility that human information processing brings to a system, and then minimize the consequence of any occasional inappropriate innovation, making it non-safety critical.

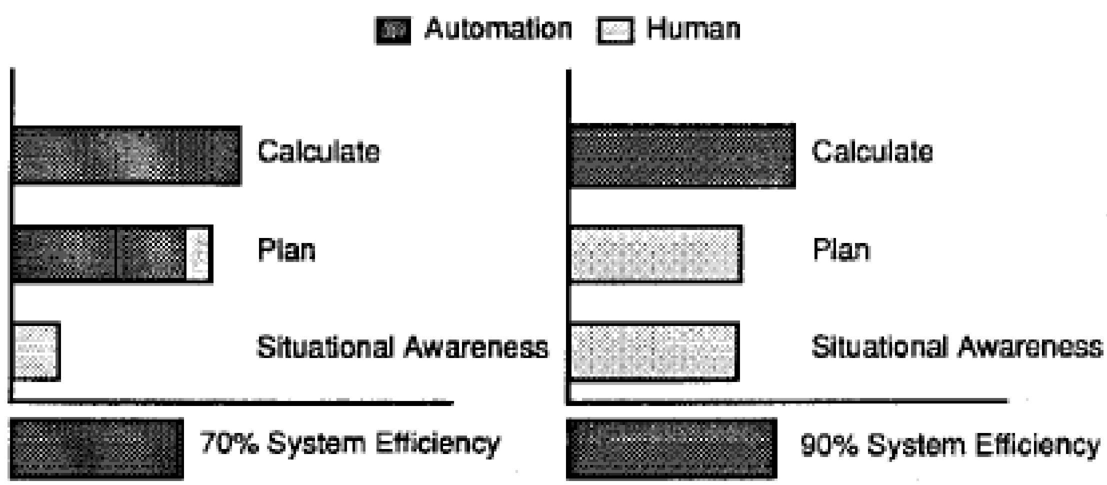

Figure 1. A Hypothetical Illustration of Overall System Efficiency Under Alternative Task Allocations

For example, the consequences of human error could be minimized for a traffic manager in two ways. First, by designing the human-computer interface to provide both feedback and other aids that lead the traffic manager to avoid errors, or otherwise to detect errors quickly and to reverse them when possible. Second, to deal with those situations when reversal is not possible, the position of the traffic manager's role within the organization is designed such that the consequences of their actions cannot jeopardize safety. The nature of such a role will be further explained in 2.3.

2.1.3 Supervisory Relationship of the Human Over the Automation

This principle postulates an interactive relationship between the human and the automation, which is modeled after the human relationship between a supervisor and a subordinate. This relationship is illustrated in figure 2.

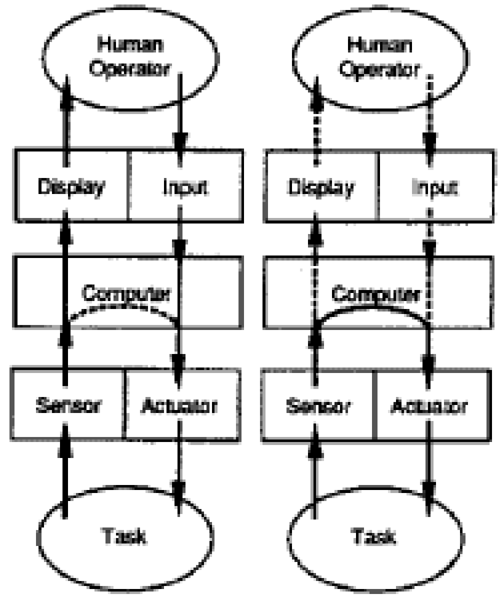

Figure 2. Supervisory Control

The dashed lines in these diagrams indicate indirect control. Thus, the left-hand diagram illustrates a situation where the automation must seek authorization from the operator before acting. In contrast, the right-hand diagram illustrates a situation where the automation can act independently on goals set by the supervisor; however, the supervisor does assess the automation's performance and can intervene to set new goals or constraints when needed. Both types of supervisory control will be incorporated in the traffic manager's role.

In the literature [5], the relationship has been called *supervisory control*, and it specifies five roles for the human operator:

- **Planning** what to do and how to do it applying human judgment, innovation, and creativity
- **Directing** the automation to implement what was planned through setting goals, parameters, and constraints for the automated control algorithms
- **Assessing** the performance of the automation in real time to ensure that the directions actually achieve planned effects without failure or error
- **Intervening** to change the goals, parameters, or constraints when desired effects are no longer occurring
- **Learning** from experience the effects of their goal, parameter, and constraint settings in order to improve future job performance

2.1.4 Hierarchical Nature of Managing Air Traffic

In addition to the three general human-computer system design principles presented above, also important to the system design is a fundamental understanding of the environment to be controlled. This subsection presents a theoretical foundation for that understanding.

The primary hypothesis is that the management of the air traffic environment can be decomposed into a hierarchy of management domains based on the quality of information at different levels of aggregation as illustrated in figure 3. Based on the work of Simon [3], this hypothesis postulates that information regarding air traffic can be partitioned into a hierarchy of quality domains. The information at higher levels in the hierarchy is composed of summary patterns of data from lower levels. These summary patterns of data are predictable over a longer time period than are the individual lower level data points from which the patterns are created. The other postulate of this hypothesis is that, based on social scientific theories of organizational structure [4], the air traffic management system should be organized hierarchically to take advantage of the air traffic environment's informational structure.

In addition, the actions taken at each scale in the management hierarchy should be appropriate for the available information. For example, strategic air traffic management functions (figure 3, middle level) would detect regions of complex interaction between different traffic flows, and act to simplify those interactions by re-routing or constraining whole flows. However, the information available at this level of aggregation could not be used to assure the separation of individual aircraft, and need not be, because the organization handles that at the tactical flight specific level (figure 3, bottom level). At the tactical flight specific level in the hierarchy, the trajectory-level information available

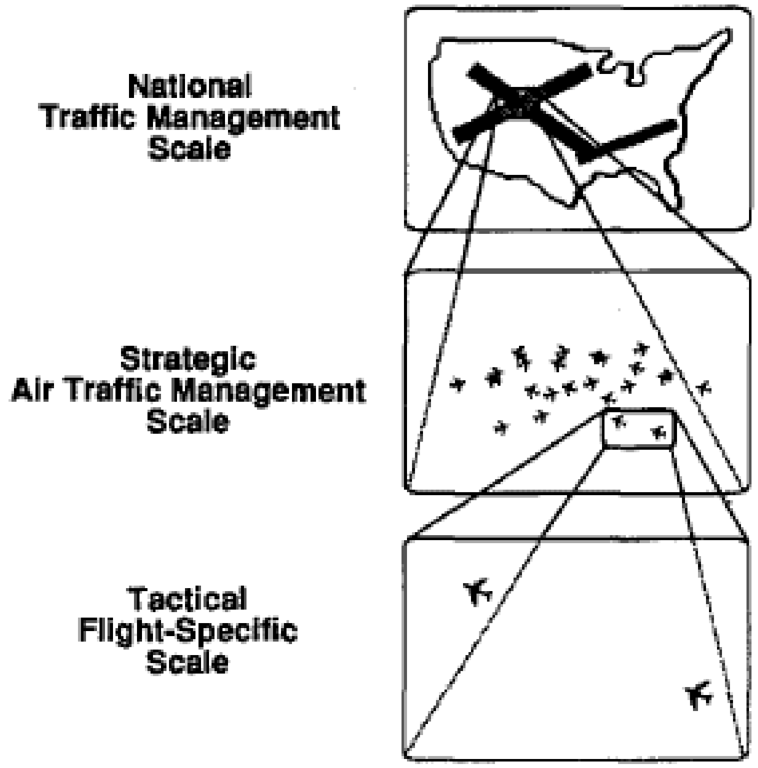

Figure 3. The Hierarchical Nature of Air Traffic

At the lowest level of aggregation, based on aircraft trajectory information, tactical flight-specific scale functions (such as separation assurance) direct and coordinate individual aircraft. At the next higher level of aggregation, based on aggregate airspace characteristic measures, the strategic air traffic management function manages local flows by directing and coordinating the flight-specific functions below. At the highest level of aggregation, based on a daily, weekly, or seasonal average of airspace characteristics, a national traffic management function provides the organizational and operational structures and constraints within which the lower management scales operate.

would be used for the flight specific functions to assure individual aircraft separation. However, the information at this level would be insufficient for flow management. At the national traffic management level, decisions would be made regarding the national structure and organization of the air traffic management system within which the lower levels operate, but information at this highest level would not support immediate responses to strategic flow management or tactical flight specific situations.

From the above discussion, it follows that flight-specific level actions taken in isolation would not take into account the consequences of these actions on aggregate traffic flows. Theoretically, such isolated actions could, therefore, result in overall system performance degradation that in turn will reduce the accommodation of collective user preferences[2]. Furthermore, it is theoretically possible that strategic traffic management actions could reduce the complexity of aircraft interactions and subsequently reduce the need for flight-specific maneuvering. The implication of these considerations is that the flight-specific functions should operate within the flow constraints set by the strategic air traffic management functions above them in the hierarchy.

2.1.5 Summary

The theoretical foundation presented in 2.1.1–2.1.4 is summarized below, and provides the basis for the description of the traffic manager's role presented in 2.3:

1. The traffic manager's role should be designed in a holistic fashion, keeping it both coherent and at the appropriate level of complexity.

2. The consequences of human error should be minimized by providing the traffic manager with planning tools and feedback. In addition, the role should be designed such that errors made by the traffic manager cannot result in safety violations.

3. The traffic manager should be a "supervisory control" role in planning strategies to resolve air traffic situations, providing the computer with directions regarding constraints to achieve those resolutions, assessing airspace complexity, and intervening to change goals or constraints. The automation does what it does best: it manipulates very large amounts of data and provides appropriate feedback to the traffic manager.

4. The air traffic management should be organized in a hierarchical fashion to match the hierarchical informational structure of the air traffic environment it manages.

2.2 THE TASK ENVIRONMENT

As illustrated in figure 3 and described in 2.1.4, the hierarchical organizational concept defines a strategic air traffic management function that will act to prevent the occurrence of air traffic situations that lead to system performance degradation. Such situations would consist of the interrelationships between various sets of aircraft and between aircraft and airspace. An example of an aircraft-aircraft situation would be the crossing of two streams

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[2] The level of accommodation would be the sum of user satisfaction with the system in enabling users to meet their objectives regarding such things as delay, fuel burn, etc.

of aircraft[3]. An example of an aircraft-airspace situation would be a single arrival stream encountering severe weather at an arrival fix.

At any given point in time, the primary activities of the air traffic management function will be to predict, analyze, and plan actions to prevent the development of such air traffic situations that may occur one-half to two hours in the future. The current concept is that human abilities will be *required* for at least some portion of these activities, some of the time: human pattern recognition for recognizing situations requiring action; creativity for developing management strategies, and judgment for evaluating alternative strategies. However, as described in 2.1.1, establishing a viable human role and an efficient system overall may require allocating to the human more than merely those tasks that require human involvement and that can not be automated.

In addition to these primary activities, others may also require human action, such as communicating with aircraft that are not equipped for direct data communication (datalink), or personally consulting with pilots in emergencies. These tasks are also currently conceived as belonging to the traffic manager; however, the details of these additional activities were not developed for this report and are left for future studies.

Extrapolating from what is known about the nature of the air traffic patterns to be managed, and applying the theoretical foundations presented in 2.1, a description of a human-computer system for strategic air traffic management was developed by the Advanced AERA Concepts program [1, 2]. What follows presents that description.

2.2.1 An Air Traffic Situation Problem Scenario

It was proposed, in 2.1.4, that air traffic situations will arise where without strategic air traffic management, actions that are taken by flight-specific functions (such as separation assurance) will result in system inefficiencies and, therefore, reduce the accommodation of collective user preferences. A description was developed using one such hypothetical air traffic situation as a focus scenario for the manager's actions.

The hypothetical example of such an air traffic situation (that has also been described in previous reports [1, 2]) is when two streams of traffic cross that will lead to a congested situation in the 50 nautical mile square region of the airspace that surrounds their intersection. The complexity of this situation is predicted to be significant 60 minutes in the future.

3 A stream could be defined, for example, by a destination airport that is common to a set of aircraft.

An examination of how such a situation appears and would be handled at the tactical flight-specific management scale and then the strategic air traffic management scale will illustrate the value conceived to be added by the strategic air traffic management.

At the tactical flight-specific management scale, the stream pattern of such a situation is not apparent (as illustrated in the bottom panel of figure 3). Therefore, the flight-specific functions (such as separation assurance) would attempt to weave the individual aircraft in the situation through the congested airspace unaware that this congestion is the result of the intersection of two streams. At the flight-specific scale the available options to reduce the congestion are also oriented around individual aircraft such as putting aircraft in holding patterns.

However, at the strategic air traffic management scale, the aggregation of flight-specific data makes the stream pattern apparent (as illustrated in the middle panel of figure 3), and stream oriented options become available. For example, a traffic management strategy could be implemented that would separate the two streams by altitude and subsequently reduce the interaction of individual aircraft. Theoretically, such a traffic management strategy could better accommodate collective user preferences and system efficiency by reducing inefficient flight-specific scale actions (such as holds) that would impede forward progress by aircraft.

The human role described in 2.3 is conceived as providing the core planning ability to this strategic air traffic management function, with the automation providing supporting tools.

2.3 THE HUMAN ROLE

It is postulated that the traffic manager will interact with a computer system capable of presenting them with a number of displays which will provide different perspectives on the state of the airspace at present and projections of the future, and will aid in the planning and evaluation of air traffic management strategies. The manager will use these displays to develop strategies to enhance the efficiency of traffic flow, to prevent air traffic situations that degrade the performance of the flight-specific functions (such as, those situations that may lead to excessive holds), and generally to improve the accommodation of collective user preferences. Fundamentally, the traffic manager's task is problem solving and their actions follow the basic problem solving model: identification, analysis, planning, implementation, and evaluation.

2.3.1 Identification

Identification is seen as involving the manager's use of a number of graphic depictions of measures of airspace characteristics[4], such as those depicted in figures 4 and 5.

Such depictions would allow the traffic manager to identify combinations of airspace characteristics which are judged to be similar to those that have been found to be associated with system performance degradation, in accord with their *assessment* role in Supervisory Control. It is expected that the subtlety and pattern complexity of these combinations will sometimes *require* human judgment and pattern recognition capabilities to identify them. Therefore, in accord with holistic system design, the manager would be regularly involved in this identification process to maintain their situational awareness and, therefore, the efficiency of the management process.

Summary data for situations under observation could be maintained on a Situation Status Display such as illustrated in figure 6.

Such a situation status display would provide the traffic manager with a high-level view of the status of all the situations and allows him or her to plan the order of required action.

The identification and addition of a situation to the situation status display could be initiated by a number of sources:

- The automation could identify regions of the airspace where it determines conditions are similar to past cases and, therefore, warrant the traffic manager's further attention.

- The traffic manager could define regions to be tracked via the summary data on the situation status display.

- Other facilities could define a region their local information indicates may lead to situations in the manager's facility that need attention.

When the automation adds a new situation, it could highlight this change to draw the manager's attention to the situation. However, this action would not be treated as an alert, rather the traffic manager could inspect the display to assess the situation's development.

In this way, in accord with holistic system design and supervisory control, the traffic manager could maintain a regular, coherent assessment and control process rather than responding to critical alerts.

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4 These airspace characteristic measures are described in more detail in *Advanced AERA Capabilities: A High Level Description* [1].

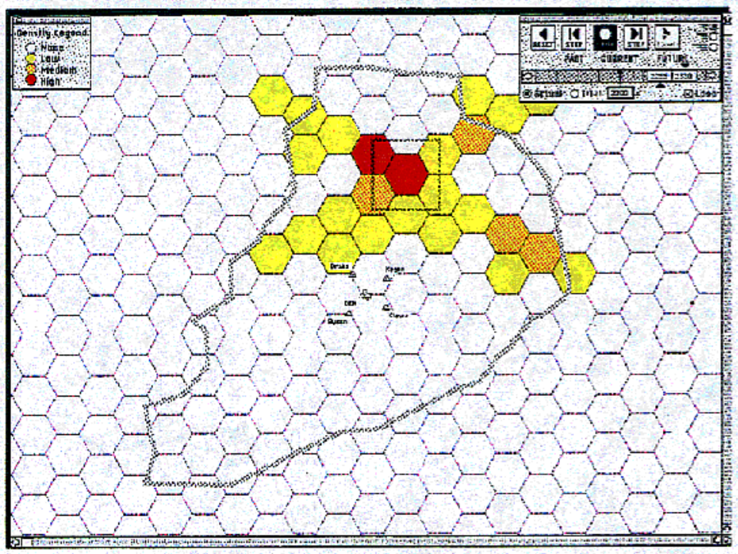

Figure 4. An Aircraft Counts View

Different types of graphics would be used to depict the current situation as well as projected future situations. This figure shows one possible type of graphic: a density map of aircraft. This display shows the density cells that are 50 nmi across. The outline of entire region encompassed by the control facility is indicated.

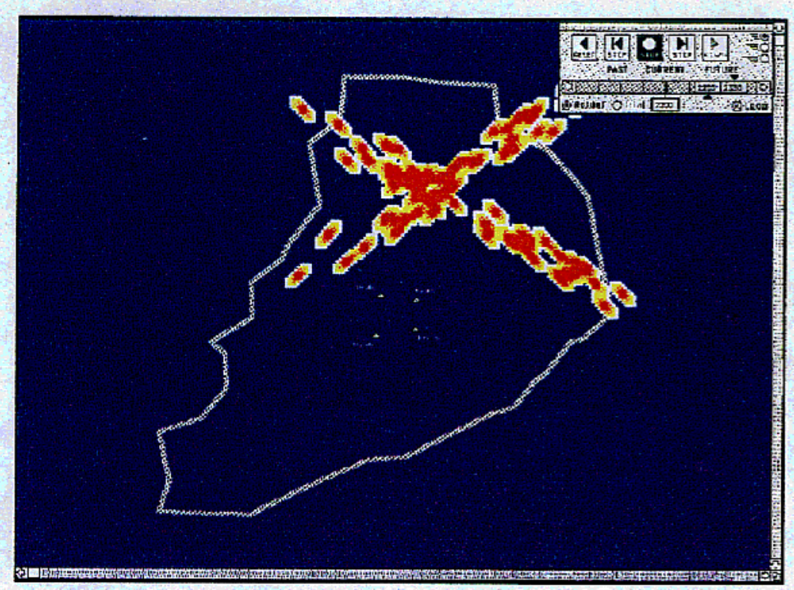

Figure 5. An Interaction View

This is an alternative view of an air traffic situation. This figure illustrates a projection of the airspace. In this view the level of interaction between aircraft is graphically visualized. Contiguous areas of red indicate areas where there is a high probability of aircraft in conflict.

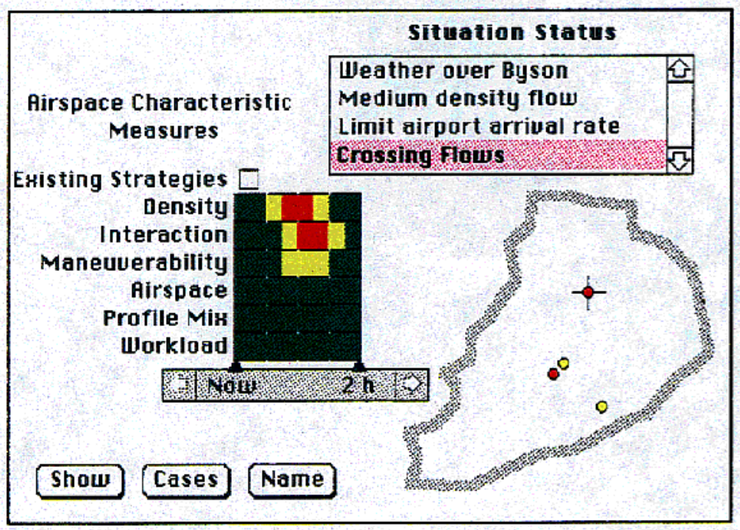

Figure 6. Situation Status Display

In the upper right-hand corner of this display, there is a list of the potential situations that have been identified. Each of these situations is located on the map with a colored circle; the color of the circle indicates the overall situation complexity. The situation that is highlighted in the list is identified on the map with a cross hair. The graphical display to the left of the map shows the level of six airspace parameters or "characteristics" over the next two hours, as they apply to the highlighted situation.

2.3.2 Analysis

Given the situations posted on the situation display, the traffic manager could determine the need for action by examining such factors as the number of aircraft involved and graphs of the expected duration and severity of the situation, which would be indicative of the likelihood of the situation and its criticality.

Situations that warrant strategic management could be analyzed in more detail again by using graphic displays like those in figure 7, which could be manipulated to isolate patterns of aircraft such as streams, sets, or fronts; and to provide information on the geometric distribution of the aircraft, and on the context of the situation.

In addition, the automation could be used to retrieve similar past cases for the manager and display comparisons with the current situation in terms of the airspace characteristic measures (as illustrated in figure 8). This would allow the traffic manager to judge which case is the most relevant to the current situation. The assumption is that past similar cases would have successful traffic management strategies associated with them, which could serve as models that the traffic manager could modify to fit the current circumstances. In this way the automation would supplement the general human expert process of bringing past experiences to bear on present problems.

The automation could use pattern matching algorithms to retrieve the similar cases, but the traffic manager would use judgment and pattern recognition to determine which is most relevant. This is in accord with the supervisory control principle of making the roles complimentary but not overlapping.

The implementation of the case-judgement task described above also illustrates the application of the holistic design principle. That principle would be violated if, instead, this task was primarily allocated to the automation, but the human needed to occasionally intervene. Such an allocation would require that different procedures be employed for situations where the automation could determine the most relevant cases versus those where it could not. For example, when the automation could make the determination, it would need to explain its judgment to the traffic manager in order to prepare the manager for planning strategies; when the automation could not make the determination, procedures for eliciting human judgment would be needed. Allocating this task to the automation would, therefore, likely lead to procedural inconsistency. Because of the resulting irregularity of the human task, such an allocation would likely reduce situational awareness, and subsequently reduce overall system efficiency.

On the other hand, the proposed task allocation of case-judgment to the human also illustrates the principle of minimizing the consequences of human error. First, none of the possible actions taken by the traffic manager can lead to jeopardizing safety: selecting the wrong case could lead to a less efficient but not an unsafe management strategy. Second,

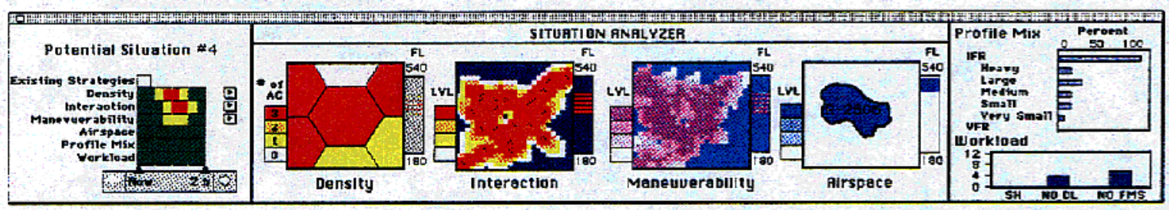

Figure 7. Display to Analyze Potential Situations and Strategies

This is an example of a display that could be used for two types of tasks: to identify the nature of a potential situation, and to evaluate possible strategies for resolving that situation. The graphical representations shown by this tool reflect the airspace characteristic measures of a region of interest. The display at the far left shows the same summary display of airspace characteristic measures as shown in the Situation Status Display. Each of these measures could be shown in further detail in other displays.

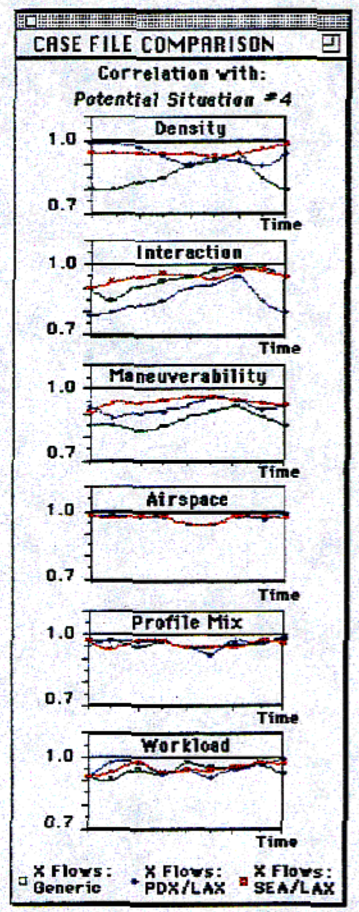

Figure 8. Planning Display Window to Compare Previous Situations

This is an example of a graphic visualization that could be used to compare the current situation with past similar situations. In this figure, the traffic manager would be presented with three previous situations that are overall the most similar to the current situation. There are six graphs, each of which represents the correlation between the current situation and the past cases for a specific airspace characteristic measure over time.

the automation support makes such an error less likely because of the aids it provides in focusing the manager's choices on only the most similar cases and in the graphic visualization provided to help clarify the comparison.

2.3.3 Planning

The automation would provide the traffic manager with the ATM strategies associated with the past relevant cases that were retrieved during the analysis phase. Most often, the traffic manager would choose to modify these strategies to fit the current situation. This planning approach is consistent with the general human expert process of problem solving. Alternatively, a new strategy could be developed if no past one is judged to be relevant enough. Figure 9 illustrates a possible display for planning that provides instantaneous

feedback as modifications are made and thus conforms to the principle of minimizing the consequences of of human errors.

A currently unresolved issue is the exact nature of the strategies needed to manage the flows of traffic at this management scale. Figure 9 illustrates one concept which is that a strategy would be a combination of flow instructions, each one specifying a flight instruction or constraint and the set of applicable aircraft. Another concept has been that strategies would take the form of *constrained airspace*. Similar to restricted airspaces, applicable aircraft would not be allowed to fly through a given constrained airspace. The planning process would result in the definition of constrained airspace maps (including start and stop times for each constrained airspace) and establishing the sets of aircraft associated with each map.

2.3.4 Implementation

The implementation process is conceived of as largely the task of the automation. Once a strategy has been defined in the planning process, the automation could translate it into the appropriate communications to the tactical flight-specific scale management (such as controllers). Actions at the flight-specific scale would then operate within the constraints set by the strategy and communicate any resulting flight changes that are needed to individual aircraft.

A currently unresolved issue is coordination with other managers and facilities. One concept is that, at this management scale, coordination could largely be part of the automated communication. The automation would post the strategies to a shared computer data area, called a *black board*. Through their computer interface, other managers (even at other facilities) would be made aware of all applicable strategies on the black board and, therefore, take them into account in their own analysis and planning processes.

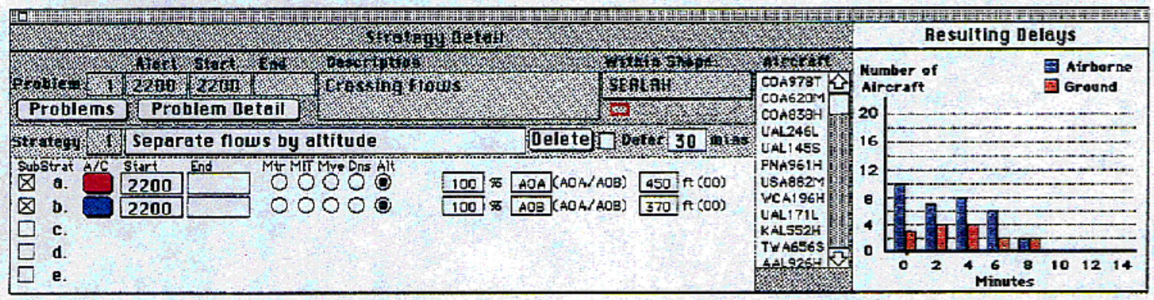

Figure 9. Planning Display Window to Create or Modify a Strategy

The "Strategy Detail" window on the left would allow the traffic manager to create a new strategy or modify the detailed parameters from a past strategy to fit the current situation. The "Resulting Delays" window on the right illustrates one use of feedback, and shows a histogram of the airborne and ground delays incurred by the strategy being developed; this histogram would be updated as the strategy parameters are modified.

2.3.5 Evaluation

It is postulated that the traffic manager's judgment will be required to evaluate past cases and, therefore, to maintain the case database used in analysis and planning. For example, judgment will be needed in determining the boundaries of a past air traffic situation: when did it start and end, what were the geographic boundaries, and what were the different sets of aircraft involved. Judgment will also be needed to determine the signature characteristics of the situation by which it can be identified and retrieved for future use. Concepts for the human-computer interface for this task have not yet been defined.

SECTION 3

BEHAVIORAL TASK ANALYSIS OUTLINE

The behavioral task analysis outline presented in this section is based on previously published reports [1, 2] as well as the description presented in section 2. Table 1 presents the behavioral task analysis which is the core of this analysis. Sections 3.1–3.5 provide additional explanation for the tasks listed in each of the five major groupings in table 1.

The purpose of this behavioral task analysis is to specify the kinds of actions taken by a traffic manager. A number of key actions can be seen throughout the task analysis and are defined below.

- **Assess:** to gather information
- **Evaluate:** to note the similarities between measurements and some standard
- **Compare:** to note the similarities between one set of measurements and another
- **Determine:** to establish the value of a measurement

Other terms are either self-explanatory or will be further explained in sections 3.1–3.5.

Table 1 presents a logical listing of the tasks, but it is not a step-by-step portrayal of the role: the sequence of tasks may not be representative, no decision points (*if-then-else*) are depicted, no cycles (*do-while, do-until*) are depicted. The basic actions have been grouped together based on the steps in the problem-solving model: identification, analysis, planning, implementation, and evaluation[5]. This model's applicability was noted in section 2. Within these groupings, tasks are listed in logical subgroups.

In addition, all of the tasks in table 1 are envisioned as taking place in a time-critical environment and are responses to frequently occurring predictions of air traffic situations, except for *Evaluation* (item 5).

3.1 IDENTIFICATION TASKS[6]

The current concept is that the traffic managers will have graphic tools, such as those illustrated in section 2, that will allow them to assess (1.1.1) depictions of projected future

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[5] As will be established in section 4, the apparent sequential ordering of these steps is psychologically tenuous. However, grouping the behavioral tasks in this manner is a convenient way for organizing this information.

[6] In sections 3.1–3.5, the parenthetical numbers refer to tasks in table 1.

Table 1. Behavioral Task Description of the Airspace Manager's Role

1 Identification

1.1 Assess and Evaluate the Visualization of Air Traffic

- 1.1.1 Assess current depictions of future interactions between aircraft patterns/sets in the airspace
- 1.1.2 Evaluate current depictions of future interactions between aircraft patterns/sets depicted as in the airspace
- 1.1.3 Assess alternative depictions of future interactions between aircraft patterns/sets
- 1.1.4 Compare future interactions between alternative definitions of aircraft patterns/sets

1.2 Observe changes made by automation to posted situations

2 Analysis

2.1 Determine Need for Action on Newest Posted Situation(s)

- 2.1.1 Assess and evaluate degree and certainty of complexity
  - 2.1.1.1 Evaluate top-level pattern of displayed predicted Air Traffic characteristics measures
  - 2.1.1.2 Assess predicted certainty of complex Air Traffic situation occurrence
    - 2.1.1.2.1 Assess predicted number of aircraft involved
    - 2.1.1.2.2 Assess predicted duration of complex situation
  - 2.1.1.3 Evaluate predicted certainty of complex Air Traffic situation occurrence
- 2.1.2 Assess, determine, and evaluate criticality of situation
  - 2.1.2.1 Determine base-line accommodation of collective user-preferences (based on no conflicts)
  - 2.1.2.2 Compare base-line with projected accommodation of collective user-preferences if situation is passed unresolved to flight-specific functions
  - 2.1.2.3 Estimate analysis/planning time
  - 2.1.2.4 Estimate resolution lead-time
  - 2.1.2.5 Determine time to action
  - 2.1.2.6 Determine criticality based on results of 2.1.2.2 and 2.1.2.5

2.2 Prioritize Situations for Action Based on Determined Need for Action

2.3 Evaluate Complex Situations in Detail

- 2.3.1 Evaluate Air Traffic Characteristic Measures in more detail
  - 2.3.1.1 Evaluate size of effected space(s) over time from each characteristic measure view
  - 2.3.1.2 Evaluate shape of effected space(s) over time from each characteristic measure view
  - 2.3.1.3 Evaluate movement of effected space(s) over time from each characteristic measure view

Table 1. Behavioral Task Description of the Airspace Manager's Role (Continued)

2.3.2 Evaluate relevance of previous cases retrieved by automation

2.3.2.1 Evaluate correlations between Air Traffic characteristics for previous cases and those for the current situation

2.3.2.2 Apply weightings to characteristics to determine most relevant case(s)

3 Planning

3.1 Determine if Strategy Constraints Associated with Similar Previous Cases Yield Relevant Planning Information for Current Case

3.1.2 Compare relevant constraints in effect outside of the ACF boundaries

3.1.3 Compare relevant constraints in effect inside of the ACF boundaries

3.2 Delimit New Groupings of Aircraft if Needed

3.2.1 Air Traffic patterns

3.2.2 Sets

3.3 Determine Satisfactory Modifications to Constraints from Strategy(s) Associated with Previous Similar Cases

3.3.1 Modify size, shape, location, and start/stop times of constrained airspace and sets/patterns of aircraft associated with constrained airspace

3.3.2 Assess change in cost resulting from modifications

3.4 Determine Satisfactory Constraints of New Strategy(s)

3.4.1 Define size, shape, location, and start/stop times of constrained airspace and sets/patterns of aircraft associated with constrained airspace

3.4.2 Assess cost resulting from definitions

3.5 Compare Predicted Outcomes of Alternative Strategies

3.5.1 Compare outcome air traffic characteristic measures

3.5.2 Compare outcome accommodation of collective user-preferences

3.6 Select Strategy for Implementation Based on Multiple Objective-Multiple Criteria Model(s)

4 Implement Strategy

4.1 Indicate Selection to Automation

Table 1. Behavioral Task Description of the Airspace Manager's Role (Concluded)

5 Evaluation

- 5.1 Select Resolved, Past, Case(s) for Retrieval
- 5.2 Define Key Characteristics
  - 5.2.1 Define signature characteristics
  - 5.2.2 Define significant points in time
- 5.3 Determine Effectiveness of Associated Strategy
  - 5.3.1 Determine effectiveness from collective-user accommodation
  - 5.3.2 Determine effectiveness regarding system costs
- 5.4 Classify Case
- 5.5 Cross-Reference Case

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air traffic patterns and sets. Evaluation (1.1.2) would entail comparing observed patterns in a given depiction with some standard(s) that are indicative of air traffic situations that lead to system performance degradation. Matches with these standards would identify the projected traffic situation as requiring further attention. The traffic manager would also be able to compare (1.1.4) traffic patterns of alternative depictions (1.1.3) to determine which depiction is most useful.

In addition, the automation may detect through its assessment of air traffic patterns that a probable air traffic situation exists and post this information for the traffic manager to observe (1.2). The automation may also post situations flagged by other ATM facilities that they have determined warrant observation.

3.2 ANALYSIS TASKS

Once situations have been identified (1) as potential air traffic situations, and the need for action has been determined for each (2.1), then the traffic manager will need to to prioritize (2.2) those situations for action. Once prioritized, the top priority situation will need to be further analyzed (2.3) in preparation of strategy planning (3).

Certain information will be readily available on displays like the Situation Status Display illustrated in section 2, and, therefore, can be evaluated (2.1.1.1) without further assessment. Other information will need to be assessed by accessing additional screens of information (2.1.1.2). Other information may require additional actions by the traffic manager (like the definition of input parameters) to be determined (2.1.2.1). Finally, some information wills the traffic manger to use the automation to develop statistical estimations (2.1.2.3).

Evaluation or comparison can be a parametric comparison between numbers (2.1.1.3, 2.1.2.2), but many of the forms of evaluation currently conceived in Advanced AERA Concepts of the traffic manager's role are more morphological in character involving the comparison of patterns (2.1.1.1, 2.3.1) and requiring visual processing.

3.3 PLANNING TASKS

The current conception of the planning process to develop ATM strategies is *case*-oriented; many of the actions involve the retrieval of previously defined strategies that are associated with relevant past cases (3.1), the modification of those strategies to fit the current situation (3.2, 3.3), and the comparison of those modified strategies (3.5). This case-orientation contrasts with the creative actions required for enumeration of new strategies for situations, although these latter activities are also included (3.4).

Current concepts suggest the use of some method to take into account the multiple-objectives of all those involved in the situation (such as, decreasing aircraft interaction and decreasing delay) and to take into account their multiple evaluative criteria (such as, those of the pilot and those of the ATM system) in the selection process (3.6). However, specific methods have not yet been defined.

3.4 IMPLEMENTATION TASKS

Actual implementation of an air traffic strategy is currently conceived as handled by the automation. With the specifications of the alternative air traffic strategies having been captured during the planning step, the traffic manager merely needs to indicate which of these air traffic strategies to implement (4.1).

3.5 EVALUATION TASKS

These tasks are not event-driven and are not time critical. It is currently conceived that the traffic manager will engage in evaluation activities when not required to attend to predicted air traffic situations. These too are computer supported tasks.

In some cases, defining key characteristics (5.2) could be an enumerative activity requiring the establishment of new characteristics by which to retrieve the case being evaluated. For other cases, it will involve selection from a list of pre-defined characteristics.

It may be that the timing pattern of event occurrences in a complex situation will be crucial to indexing it for retrieval. If so, then task 5.2.2 may require the pattern recognition/visual judgment of the traffic manager to define the *edges* (start/stop times) of these occurrences.

As did the selection of a strategy (3.6), determining the effectiveness of a strategy (5.3) will be a multiple objective—multiple criteria determination process.

Both classifying and cross-referencing cases are enumerative types of activities requiring judgment and creativity.

3.6 CONCLUSIONS

The behavioral tasks outlined in table 1 primarily involve cognitive behaviors as opposed to observable motor behaviors. In addition, a significant portion of these tasks involve visual/spatial evaluation of pattern-shapes, as opposed to the evaluating lists of words or numbers. Others of these tasks involve the enumeration of alternatives. Both the visual/spatial processing of patterns and enumeration are human judgment tasks.

The cognitive judgment nature of these tasks means that the major human factors issues relevant to the traffic manager's role involve the nature of the mental processes required to perform these tasks. Section 4 describes a framework for and models of these mental processes.

SECTION 4

APPLICABLE COGNITIVE PSYCHOLOGY FRAMEWORKS AND THEORIES

From the operational and behavioral descriptions of the traffic manager's role in sections 2 and 3, a number of factors can be discerned that indicate applicable cognitive psychological frameworks and theories. These frameworks and theories in turn reveal the issues described in section 5 and provide the conceptual structures for empirical research that is outlined in section 6 to address those issues. The following factors are apparent from the previous descriptions, and the relevant links to the psychological literature are in bold-typeface.

- The core function of the traffic manager is **problem solving** to prevent predicted air traffic situations that may lead to performance degradation. Their actions follow the basic problem solving model: identification, analysis, planning, implementation, evaluation.

- The problem-solving environment is **event-driven**. The characteristics of the identified predicted air traffic situations determine the actions of the traffic manager.

- **Visual/spatial cognitive processes** are used throughout the traffic manager's tasks. The current design of the displays for this task is a result of this factor not a cause. For example, the current conception of airspace complexity is that it can best be described by a pattern of airspace characteristic measures that can not be linearly combined and that are correlated. The graphic iconic display of this pattern illustrated in figure 4 on the Situation Status Display is a recognition of this conception.

- The problem-solving environment is **probabilistic**; meaning that the future state of the environment cannot be perfectly predicted and therefore involves **decision-making under uncertainty**. The resolution actions of the traffic manager must precede the actual occurrence of the problem and, therefore, they must react to the statistical prediction of such problem's future occurrence. Subsequently, evaluation of the success or failure of the implementation of a resolution strategy is problematic: if the action is successful then no air traffic situation will occur, on the other hand, even without the strategy, simply by chance, a situation may still not have occurred. Therefore, even after the fact, it is not possible to establish whether the action was actually needed. However, failure to act when needed will be readily identifiable after the fact, because an air traffic situation will indeed occur.

- The problem solving environment involves **multiple objectives and multiple criteria** requiring **decision-making under complexity**. For example, the traffic manager may be trying to fulfill the multiple objectives of decreasing the interaction of streams of aircraft and concurrently decreasing the collective delay of aircraft. In meeting such objectives the traffic manager may be also trying to meet multiple criteria of the pilot, the airline, the passengers, and the ATM system.

- Even though the problems to be resolved are in the future, actions must be taken in the present (or near future). Sets and patterns of aircraft managed by the traffic manager are likely to respond slowly to ATM strategies. Therefore, these strategies must be implemented with enough lead-time to be effective. The length of lead-time and analysis/planning-time will determine how soon action must begin. For example, if a problem is predicted to commence 60 minutes in the future, and the required lead-time is 50 minutes, and the analysis/planning takes 10 minutes, then action must begin immediately.

  Therefore, even though the problems to be resolved are in the future, actions may need to be taken in quick succession. If air traffic problems occur frequently, then so will the problem predictions to which the traffic manager will be responding. Subsequently, given this fact and that actions must be taken in the present, it is possible that **the traffic manager will need to be continuously responding**.

Section 4.1 presents a general cognitive framework which provides a structure for describing **problem-solving** cognitive activities. Section 4.2 presents a model which addresses the **event-driven visual/spatial** aspect of the air traffic manager's task. Section 4.3 presents an overview of findings in the psychological literature regarding **human decision making in complex and probabilistic environments.**

4.1 A GENERAL COGNITIVE FRAMEWORK

This framework is provided by John Anderson's theory of cognitive architecture, ACT*[8]. ACT stands for Adaptive Control of Thought and is a *production-system* theory of cognition. Anderson, states that "no other psychological theories have been as precise and detailed in their modeling of cognitive tasks" as production-system theories.

These theories propose that human cognition can be described in terms of a set of condition-action pairs called productions. The condition specifies some pattern of data, and if elements in the working environment match these patterns then the action specified in the production can be taken. This construction is similar to the general category of *pattern-directed* systems in computer science which include *knowledge-based*, *expert*, and *case-based* systems.

The constructs of ACT* coincide with the traffic manager's domain in a number of ways. First, the emphasis on pattern matching in the ACT* framework coincides with the visual/spatial nature of the tasks described in section 3. Second, the condition-action foundation of production-system theories like ACT* provides these theories with an event-driven perspective which coincides with the event-driven real-time problem-solving nature noted in section 2.3.

Beyond these direct connections with the traffic manager's domain ACT* is claimed to be capable of modeling all cognitive activity and provides a detailed architectural structure for examining such activity.

The major structural components of the ACT* framework diagrammed in figure 10 are three memories: *declarative, production, and working.*

- *Declarative memory* contains a network structure of *cognitive units.* These units can be propositions (*traffic is dense*), strings (*AAL123, DAL456*), or spatial images (*contiguous red area surrounded by blue*). In each case a cognitive unit encodes a set of elements in a particular relationship.

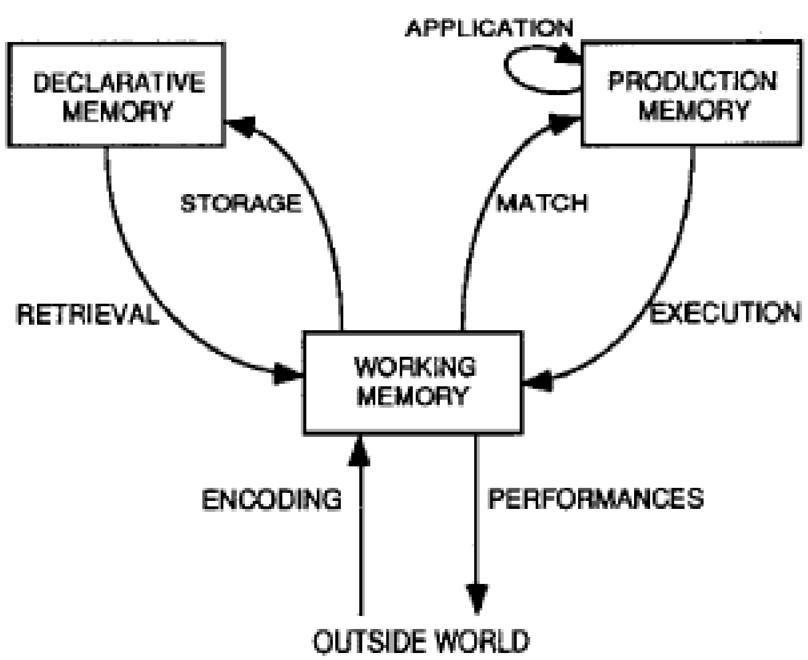

Figure 10. A General Diagram of Anderson's ACT Cognitive Architecture

- *Production memory* contains the set of condition-action pairs which define procedural knowledge (*if congestion exists and crossing streams are involved, then stratify one stream by altitude*).

- *Working memory* contains the information that the cognitive system can currently access.

Almost all processes in the general ACT* framework involve working memory.

- *Encoding* deposits information regarding the outside world into working memory.

- *Matching* compares data in working memory with the conditions of productions.

- *Execution* deposits the actions of matched productions into working memory.

- *Storage* can create permanent cognitive units in declarative memory from the data in working memory.

- *Retrieval* brings information from declarative memory into working memory.

- *Performance* converts commands in working memory into behavior.

The *application* process, which is the process where new productions are learned from studying the history of application of existing productions, is the only process that does not involve working memory.

Of all the cognitive processes in the ACT* framework, *match*ing is key to the production system architecture because it is claimed that pattern matching underlies all varieties of cognition, providing its data-driven quality.

A complete description of the traffic manager's role in terms of ACT* model is beyond the scope of the present paper. Such work is the equivalent of creating an expert system to perform the traffic manager's task. Not only is this a large undertaking, but current knowledge is not complete enough for such an undertaking, as is outlined in section 5. However, this framework provides useful constructs for discussing the human factors issues that need to be addressed.

For example, the memory structure defines that parameters regarding three types of required information must be determined:

- Static data, like the location of airspace resources, that are stored in declarative memory.

- Dynamic data, like interrelationships between the current patterns of traffic, stored in working memory.

- Procedural data, like what actions to take when certain interrelationships are observed in the location of certain airspace resources, stored in production memory.

This memory structure also implies that the capacities of these memories relative to the informational requirements of the environment is significant for human performance and defining the level of automated support required.

Additional issues raised by this framework are discussed in section 5.

With ACT* providing a general cognitive framework, insights into the application of this framework to the traffic manager's domain come from additional work in cognitive psychology described in sections 4.2 and 4.3.

4.2 VISUAL/SPATIAL COGNITIVE PROCESSES

The *exploration cycle* model of Ulric Neisser [9] specifically addresses the event-driven visual/spatial aspect of the traffic manager's task domain. Figure 11 illustrates the framework of this cycle of exploration and information perception.

Neisser makes clear that cognition, perception, and what is being perceived are inseparable. The inner ring in the diagram represents the local perceptual cycle. In this cycle, at each moment, people rely on past knowledge in constructing anticipations of what will be perceived. These anticipations also will enable a person to (in ACT* terms) *encode* the perception when it becomes available. In addition, in order to make this information available, *performance* of behavior (in ACT* terms) can also be directed by these anticipations. The outcome of the performance of this behavior is the encoding of information which in turn modifies the knowledge that is relied on for the construction of anticipations. Thus modified, this knowledge directs the construction of new anticipations for further exploration, and the knowledge structure becomes ready for more information.

This cycle is embedded within the more global exploration cycle that is occurring in parallel, and which is represented by the darker gray areas outside the circle in figure 11.

It is critical to Neisser's construction that the processes of anticipation, encoding, and performance of exploration are not sequential. Even the term cycle implies more order than the mental oscillations between processes that is envisioned by Neisser.

Neisser [9] illustrates the interaction of cognition, perception, and environment in a description of playing the game of chess. Master chess players succeed because they

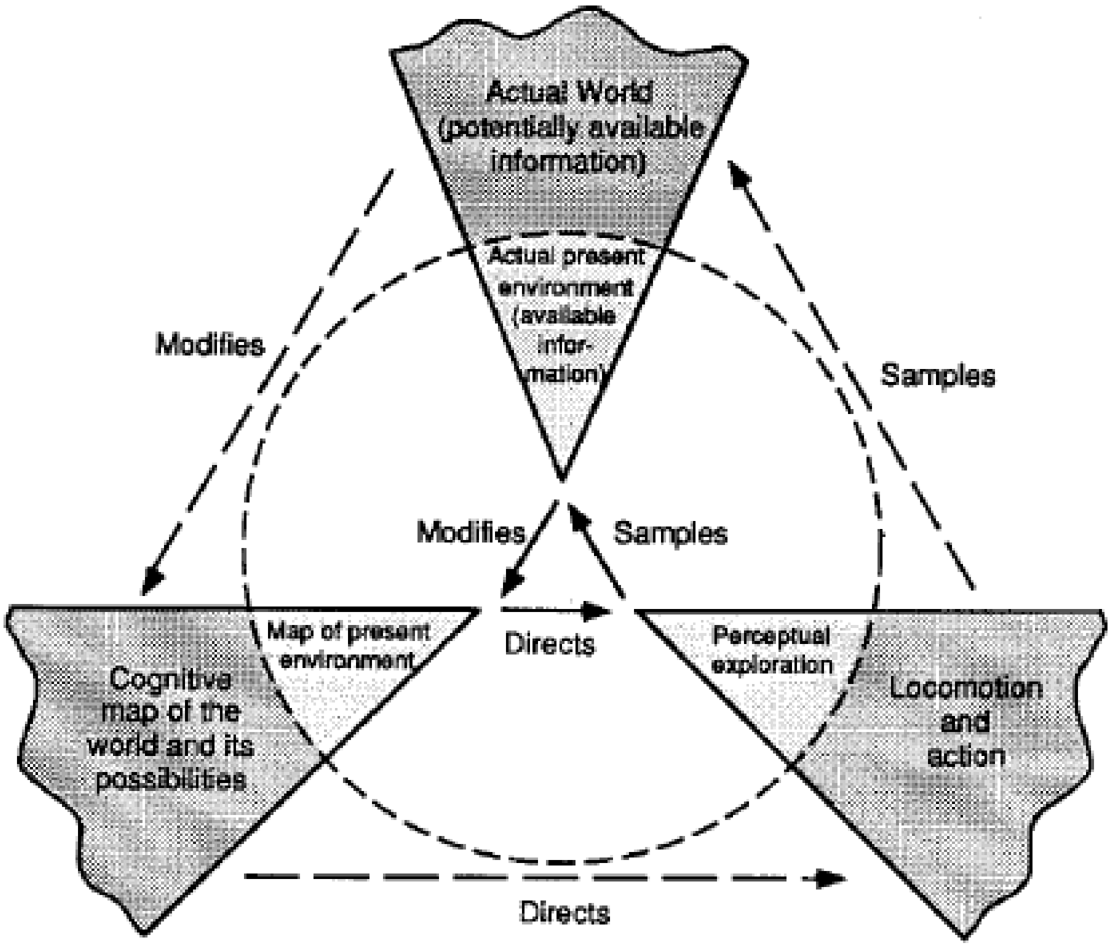

Figure 11. Neisser's Exploration Cycle

perceive aspects of the position of pieces that escape a lesser player. Structural aspects of the relationships between the positions of some pieces constrain for the master the locations of other pieces. It has been estimated that chess masters have a vocabulary of piece constellations about as large as most people's verbal vocabulary. The information from the chessboard not only directs the masters next moves but also where they move their eyes. A master quite literally *sees* a chess position more comprehensively than a novice or non-player. Clearly, the information that specifies the next proper move is available in the light sampled by a baby as by a master, but only the master is equipped to pick it up. Furthermore, these piece constellations and the rules of chess do not control a masters perception; they make incisive perception possible by giving them something to perceive.

> Such an interpretation suggests that the chess player is neither totally free to look and move where he chooses nor entirely at the mercy of his environment. The control of eye movements and all adaptive behavior is only comprehensible as an interaction [9].

Applying the exploration cycle concepts to the current concept of the traffic manager's role, suggests that several visual vocabularies will need to be acquired:

- Patterns of set-interactions, which are formed by mapping sets of aircraft in the airspace.
- Patterns that are indicative of air traffic situations that lead to system performance degradations, and the associated patterns of values of airspace characteristic measures.
- Patterns that indicate the type of ATM strategy to be employed, which are formed by the mapping of individual characteristics across the airspace over time.

This exploration cycle model emphasizes that a significant element in determining the human requirements for the traffic manager's role is a comparison between the informational character of the airspace management environment and the traffic manager's cognitive capacities for such visual vocabularies. Specific research questions regarding this area are outlined in section 5.

4.3 COGNITIVE PROCESSES IN COMPLEX PROBABILISTIC ENVIRONMENTS

Substantial deficiencies have been found regarding human decision-making in a complex probabilistic environment such as that defined for the traffic manager. These deficiencies have implications for the type of computer-aiding and feedback needed to minimize the consequences of human error in this type of ATM. Klein [10] presents an extensive review of the relevant research that is summarized below:

- People often fail to correctly take into account the statistical notions of randomness, variance, and variability. For example, people not only fail to understand the relationship between sample sizes and variance, but often believe conversely that smaller samples have less variance and are hence more reliable. This phenomenon could manifest itself in ATM in the overvaluing of successful, but not extensively used strategies, or the premature abandoning of unsuccessful, but otherwise correct strategies.

- People frequently do not appropriately revise predictions in light of new information. They often fail to take into account baseline probabilities, or overvalue intuitively persuasive but statistically insignificant information. In the ATM tasks this could lead to the selection of a strategy based on intuitive but irrelevant air traffic situation characteristics, such as focusing on the destination of a traffic stream instead of the actual patterns of traffic.

- Intuitive analyses lead people to misconceive concepts regarding probability and make people insensitive to such concepts. An example is the "gambler's fallacy" where after observing a long run of red on a roulette wheel, most people believe that black is now due. When the environment is complex enough or the cues are subtle enough, statistical experts will make the same types of predictable errors as non-experts. For example, after seeing predictions of inclement weather fail a number of times, a traffic manager may overvalue the probability of the next prediction that is *now due* to be realized.

- People heuristically simplify probabilistic complex problems and in doing so eliminate or misconstrue significant details. They also show heuristic biases in evaluating outcomes. This has implications for the design of displays to help make air traffic situations comprehensible and to make significant details salient.

- The probabilistic nature of an environment can prevent people from ever understanding the functional relationship between factors in the environment. This happens because the factors noted above prevent people from appropriately interpreting the meaning of outcomes in complex probabilistic environments. This leads to the development of *superstitions* (the attributing causal effects to irrelevant coincidences).

Research conducted by Klein [10] showed that, in such environments, people prefer courses of action that agree with their intuition, even when their intuition is demonstrably wrong. The research also showed that people's confidence in a problem analysis is most greatly effected by whether the course of action recommended by the analysis is intuitively agreeable as opposed to whether the analysis is complex. Furthermore, it appeared that if an intuitive course of action is not explicitly challenged in a complex problem situation, then that course of action is readily accepted even when it is simplistic and normatively wrong.

SECTION 5

RESEARCH QUESTIONS

The operational and behavioral descriptions, and the subsequent cognitive psychology frameworks and theories provide conceptual structures not only for detailing what we do know, but complementarily, for indicating where further research is required to complete our understanding of the human role in a more highly automated system.

The current conception of the primary human role in a highly automated ATM system that is described in previous sections can be summarized as a problem-solving task regarding the planning of ATM strategies that will prevent the occurrence of predicted air traffic situations, and subsequently prevent system performance degradation. This conception has been based on a hypothetical scenario and theories regarding the airspace environment. The *actual* informational requirements of such an environment in comparison with the cognitive capacities of people aided by automation needs to be more concretely, empirically established.

Questions remain regarding the level and type of automation needed for the ATM, what the nature of the human interaction with that automation will be, and at the base of all these considerations are questions regarding the match between the informational characteristics of the environment and human information processing capacities. Answers to these questions are essential to answering human resource questions regarding such areas as staff selection, training, and procedures.

Section 5.1 presents research questions regarding the information requirements of the environment. Section 5.2 presents research questions regarding human cognitive capacities and the human-computer interface. Section 5.3 presents a summary of the issues raised.

5.1 ENVIRONMENTAL INFORMATION REQUIREMENTS

5.1.1 The Nature of Events in the Environment

What types of air traffic situations yield occurrences of system performance degradation?

> The strategic ATM role that is postulated in this report assumes the existence of such air traffic situations. This is implied by the hypothesized hierarchical nature of air traffic.
>
> Furthermore, from an operational perspective, the answer to this question is fundamental and will determine the nature of the strategic ATM role. Obviously, if there are no realistic air traffic situations which yield degraded performance, and,

therefore, in which strategic management could improve system performance, then the current conception of the role of strategic ATM and the human role in that management needs to be changed.

Currently, the nature of performance degrading air traffic situations has been qualitatively described, as in this report and others [1, 2]. However, empirical data does not exist regarding either the actual existence of such situations in the air traffic environment (such as performance degrading crossing flows), or their effect if they do exist (such as weather). Research is needed to determine if under circumstances that are representative of the future air traffic environment, there will be air traffic situations where the tactical actions of flight specific scale functions (such as separation assurance) result in occurrences of less satisfactory accommodation of collective user-preferences than when such functions are supported by more strategic ATM of those situations.

Assuming that management strategies may be related to the nature of the such air traffic situations, answers to the following questions would also be important:

- Are there common flight-specific characteristics in such situations?
- Are there particular patterns of traffic that yield such situations?
- Can classes of these situations be established?

What is the pattern of occurrence of system performance degradation?

The frequency of these occurrences in comparison with the system capacity to manage them has significant implications for the hypothesized operational design of strategic ATM functions.

Regarding overall system design, the frequency of these occurrences has the following implications:

- At a low level of frequency, it may not be cost-effective to develop a system to handle essentially non-safety related situations. If unsatisfactory accommodation of collective user preferences occurs only rarely, is this unsatisfactory overall?
- At a moderate level of frequency, it seems appropriate to apply the current problem-solving design concept that is described in this report.
- At a high level of frequency, a dynamic control approach may be more appropriate than the problem-solving approach described in this report. In a

dynamic control approach, traffic managers and automation would continually adjust airspace constraints in order to keep the pattern of values of airspace characteristic measures within established boundaries.

Regarding the human-computer interface:

- At a low level of frequency, interface design issues arise, in terms of the ACT* framework, regarding maintaining the strength of cognitive elements in declarative memory, of productions in production-memory, and of elements in working memory (situational awareness).

- At a high level of frequency, cognitive issues arise regarding the capacities of cognitive processes, and in Neisser's terms the capacity of the perceptual cycle for interacting with the automation. The resolution of such cognitive issues may raise operational issues regarding procedures for distributing workload across staff and subsequently procedures for coordination.

The above considerations make it clear that the answer to this question has significant implications for overall system design and for human resource requirements for such areas as staff selection, training, and procedures.

5.1.2 The Complex Nature of the Environment

Are there characteristic airspace conditions that are indicative of the occurrence of system performance degradation?

An analogy can be drawn with meteorology. Questions 1.1 and 1.2 analogously ask, "Do thunderstorms occur?" and "What is the pattern of their occurrence?" The current question is analogously asking "What are the weather conditions surrounding thunderstorms at the time of their occurrence?"

The current six hypothesized airspace characteristic measures described in *An Evolution of the Human Role in the En Route Air Traffic Management System* [2] need to be tested for diagnosticity against realistic circumstances. If inadequate, then additional or substitute measures need to be devised.

The number of measures needed, and the manner in which they must be combined have significant implications for operational design and its relation to the elements of cognitive capacity of a human traffic manager as described in ACT*.

What are the characteristics for discriminating between different classes of complex ATM situations?

Assuming different classes of situations can be identified, is there sufficient information in the surrounding conditions to predict which class will occur based on airspace characteristic measures? Given the problem-solving focus of the ATM task, different classes may require different traffic management strategies. Determining which solution strategy is appropriate may need to be done with some lead-time to allow for effective implementation.

The number and interrelationship of characteristics for class prediction would have significant implications for operational design in relation to the cognitive capacities of the human traffic manager.

What is the number of different classes of complex situations?

This too has implications for operational design, given its relationship to the traffic manager's memory and processing capacities.

What is the nature of the ATM strategies needed to resolve traffic situations which lead to occurrences of system performance degradation?

Given that an ATM strategy is a set of flow instructions:

- How many instructions will be necessary to implement effective strategies?
- How complex (or detailed) will the applicability criteria need to be?
- How complex will the constraints need to be?
- To what degree will the instructions in the set differ from each other in applicability criteria and constraints?
- How complex will the pattern of start and stop times be for the set of instructions.

Answers to these questions will help determine whether enough lead-time can be provided to allow for effective management of the air traffic. Other parts of this determination are the responsiveness of the environment to changes in constraints, and the time requirements for predicting performance degradation occurrences.

In relation to the traffic manager's cognitive capacities, operational design will be significantly affected by how complex the strategies must be and the form they take. Strategy complexity and form will also affect planning time.

5.1.3 The Probabilistic Nature of the Environment

Given that indicative characteristic conditions can be determined, are there predictive conditions? What amount of lead-time can be given?

> Using the weather analogy, "Are there conditions in advance of the thunderstorm which will indicate that one is likely to form?" and "How far in advance can such predictions be made?"
>
> Building on this analogy, it will also need to be determined if there is a relationship between this lead time and the type of the situation to be predicted, as is the case for storms. Furthermore, will conditions that predict a situation appear suddenly, or will they gradually build?
>
> The answer to this question is part of determining whether enough lead-time can be provided to allow for effective regulation of the air traffic. The responsiveness of the environment to changes in constraints and the planning time requirements of the traffic manager are other parts of this determination. These parts are addressed below in this section and in 5.2.2.
>
> Once again, the level of complexity of making predictions interacts with the cognitive capacities of the human traffic manager and will affect the operational design of the human role.
>
> In addition to the above considerations, the distribution pattern of the occurrence of these air traffic situations may be relevant to their predictability. Extrapolating from recent work on self-similar fractal patterns in other dynamically controlled systems suggests that, in this ATM system, the longer time-scale pattern of these air traffic situations may resemble patterns of related events at shorter time-scales rather than a random distribution.

How uncertain are the predicted air traffic patterns and sets in the airspace?

> If these patterns and sets are not stable across the half-hour to two-hour timeframe established as the domain for strategic ATM, then management of these objects within that timeframe cannot be maintained. More stable objects will need to be devised or the strategic management concept re-evaluated.

What are the response characteristics of the air traffic patterns to changes in ATM strategies?

> The medium of control of the ATM system over air traffic is communication with individual flights. The response of these flights to direction from the system has a

degree of uncertainty, and the relation of an individual flight to a given pattern of traffic is probabilistic. Therefore, control of air traffic patterns is through an uncertain chain of events and this probabilistic nature will effect how quickly and predictably changes can be made.

The quickness of response is significant for lead-time requirements.

The predictability of changes has significant implications for the overall management concept. The functional relationship between changes in constraints and degree of response is significant to the manageability of the the system. For example, if this function is chaotic in nature, then strategic management may not be viable.

Furthermore, given the probabilistic relationship between strategies and air traffic responses it may be difficult to determine when further fine tuning of management strategies at the strategic ATM scale is no longer beneficial.

The interaction between response quickness and response predictability also has significant implications. If the speed of response is slow, then it will be difficult to determine in a timely fashion the actual effects of strategies. Given that the patterns being managed are statistical projections then the precision of predictions based on these statistics needs to be determined. This has implications for planning time regarding being able to determine when sufficient planning has been accomplished.

Given this probabilistic environment, how can the performance of the traffic manager be evaluated?

Given the probabilistic nature of the environment, the success or failure of specific management actions can be merely a result of chance in any single instance. This has implications for providing the traffic manager with adequate feedback to minimize the consequences of errors and to provide psychological closure (addressed below).

5.2 HUMAN COGNITIVE CAPACITIES AND THE HUMAN-COMPUTER INTERFACE

Of all the strategic ATM tasks, which tasks *must* be performed by people?

This is of course *the* fundamental human resource question. In accord with the holistic design principal (section 2.1.1), the traffic manager's tasks should be coherent, and performed on a regular basis at an appropriate level of complexity. To achieve this, first, tasks *requiring* human performance must be determined.

Such requirements may be based on operational necessity, but also may be based on organizational or political needs. Next, to achieve overall system efficiency, and on the basis of achieving coherence, regular performance, and appropriate task complexity, it must be determined what additional tasks must be allocated to the traffic manager and designed for human performance.

Specific questions in the following subsections, attempt to answer this general fundamental question.

5.2.1 Managing Events

The following two questions assume that human abilities are required for the problem-solving tasks of air traffic management.

If the frequency of complex air traffic situations are low, what automated support will be required to maintain situational awareness?

In accord with the psychological literature regarding memory, ACT* predicts that unused cognitive units in declarative memory, and unused productions in production memory will decrease in activation strength and hence take longer to retrieve when needed. In addition, the environment will need to be sampled to encode information into working memory. Neisser's model suggests that the efficiency of this encoding will also be diminished because (in ACT* terms) of the reduced activation strength of the productions guiding the sampling behavior. Given this *forgetting curve* some manner of automated support will be required to maintain situational awareness.

If the frequency of complex air traffic situations is high, what automated support will facilitate the quick disposition of situations?

This question can not be answered in isolation, but rather its answer will be shaped by the answers to additional questions below.

5.2.2 Managing Complexity

Does it require human abilities to discern the pattern of characteristics that differentiate air traffic situations that lead to system performance degradation?

Even with powerful automation tools, some pattern recognition tasks still require unique human pattern recognition abilities and judgment. Today examples include finger print identification, connected speech recognition, and judging the goodness of photo enhancement. The answer to this question will determine whether this task operationally requires human involvement.

How can the characteristics be displayed to facilitate human discrimination between different classes of ATM situations? How can planning information be displayed to facilitate human development of complex ATM strategies and to evaluate them under multiple objective and multiple criteria?

> The graphic visualization can provide powerful tools for reasoning about quantitative information [Tufte, 11]. Human understanding of such complex areas as chaos theory has recently been greatly facilitated by the advent of computer visualization. Empirical research is needed to determine the most useful representations of air traffic data, especially given the known difficulties people have regarding decision-making under uncertainty and complexity (see section 4.3). In addition, data needs to be collected on analysis and planning time requirements to determine operational feasibility given planning time requirements.

In a future air traffic environment, what will be the group dynamics of a traffic management team in coping with complex air traffic situations?

> The organizational solution to dealing with an overload of complexity is to decompose the environment into manageable units, and distribute the load. If complexity of the environment leads to decomposing problems, how will this be accomplished? How will tasks be allocated among people? How will the actions of these people be coordinated?

5.2.3 Managing Under Uncertainty

How can psychological closure be provided to the traffic manager regarding the development and implementation of ATM strategies in a probabilistic environment?

> If the speed of response is slow, then it will be difficult to determine in a timely fashion the actual effects of strategies. This has implications for being able to determine when sufficient planning has been accomplished. It also has implications for providing performance feedback to the traffic manager because the value of immediate outcomes is problematic.

How do you provide useful performance feedback to a traffic manager in a probabilistic environment?

> The key to improving performance on any task is the availability of relevant feedback. The ACT* *application* process where new productions are learned, assumes the availability of an outcome history of old productions. However, in a probabilistic environment, individual outcomes do not provide unequivocal feedback on management strategies: good strategies can have bad results by chance, and conversely bad strategies can have good results.

5.3 SUMMARY

Regarding the specific nature of the task environment and the traffic manager's cognitive capacities, the preceding sections raise many questions that must be answered to complete an understanding of the human resources requirements for operational procedures, staff selection, training, and performance evaluation. Section 6 provides a research plan for answering these questions.

SECTION 6

RESEARCH PLAN

A detailed research plan is beyond the scope of this report. However, general approaches can be specified. Section 6.1 describes two methods for analyzing human factor requirements. Section 6.2 outlines the steps of a progressive research plan.

6.1 TWO METHODS FOR ANALYZING HUMAN FACTOR REQUIREMENTS

6.1.1 Strategic Job Analysis

Strategic job analysis is one method that has been described [12] for analyzing the task environment and human capacities needed for jobs that are likely to change as a result of increasing automation. The process involves assessing current jobs and then conducting interviews with subject matter experts to identify significant areas of change. Existing task environment and human capacity descriptions can then be revised to reflect these future changes.

This approach is not applicable to analyzing the traffic manager role that is described in the present report for two reasons.

First, the qualitative differences between the current concepts of the traffic manager's role and current roles in ATC suggest that extrapolation from current roles is not useful. The general types of activities of the traffic manager are performed today. However, in today's organizational structure, and with today's tools, the performance of these activities is largely reactive, too late, too flight specific, and, therefore, involves moving aircraft unnecessarily. With the organizational structure and tools for the traffic manager described in this report, the performance of these activities becomes proactive, predictive, and deals with aggregate objects that are not aircraft. These differences severely limit the relevance of past ATC experience to the traffic manager's role.

Second, as indicated in the previous section, our current conception of the traffic manager's role is still too incomplete in many respects. For example, we do not know how the aggregate objects will be defined or behave, and past experience is not applicable. Even if there were relevant current roles in ATC, not enough is known about future changes to the system to allow the proper identification of significant areas of change, nor to subsequently revise the descriptions of current tasks and human capacities.

6.1.2 Simulation

A second method is to develop computer-based simulations which embody the known factors of the environment, human capacities, and the human-computer interface, and will enable the analysis of the complex interaction between these factors.

For a simple example, a simulation could be developed to examine only environmental factors. Such a simulation would embody:

- Flight schedules based on today's distribution of departures and arrivals but with increased numbers of flights to reflect the currently projected increase

- User-preferred direct trajectories

Flight trajectories would then be simulated based on these schedules and user-preferences, and then the resulting traffic patterns could be evaluated.

This approach could also be applied to examining in isolation relevant human capacities. This would allow for testing such capacities even before complete details were known about the airspace environment. For example, a supervisory control simulation has previously been developed that analyzed workload and performance [13]. The simulation allowed for human interaction with abstract tasks that embodied the fundamental characteristics of the supervisory control environment. It also allowed for the manipulation of these characteristics (such as the number of discrete tasks, and their frequency) and subsequent analysis of the effect of this manipulation on performance and workload.

The research questions specified in section 5 seem most amenable to this general computer-based simulation approach. Section 6.2 describes a research plan that progresses from establishing fundamental knowledge in a relatively controlled environment to providing operational knowledge in an environment with a high degree of fidelity to the real-world.

6.2 PROGRESSIVE RESEARCH PLAN

6.2.1 Control vs. Fidelity

There is a tradeoff between the fidelity of the research environment to the real-world and the degree of experimental control that can be established. There are costs and benefits for establishing environmental fidelity and for experimental control. The following sections describe a progressive research plan that attempts to exact the greatest benefit for the cost at each step.

It is axiomatic that the real-world is extremely complex. It is also axiomatic that the scientific method requires control over all but experimental factors of interest so that the causes of experimental outcomes can be clearly established. There is then a technical conflict between establishing necessary scientific control and establishing real-world fidelity.

One approach to resolving this conflict has been to develop a progressive research plan. Such a plan seeks to first establish fundamental knowledge under rigorously controlled environments. Establishing such knowledge then allows for the progressive introduction of greater real-world fidelity and complexity into subsequent research experiments while maintaining a clear cause-effect relationship through the insights provided by the prior research in more controlled environments.

Such a progressive plan also has a cost benefit. Developing environments with high real-world fidelity is relatively expensive. A progressive approach limits up-front expenditures until better information is available to indicate the feasibility of the research direction.

The human factor areas requiring further research lend themselves to such an approach. This is indicated by the range of questions in section 5 which go from fundamental (do ATM strategies improve efficiency in 5.1.1) to operational (how should airspace characteristics be displayed in 5.2.2).

6.2.2 General Proposal

It is clear from section 5 that before human resource questions regarding areas such as staffing selection, training, and procedures can be addressed, more fundamental questions must be answered regarding the informational nature of the task environment and the cognitive capacities of the traffic manager.

Regarding the primary nature of the task environment, a simulation should be developed to establish the nature of air traffic patterns in the 2010 timeframe.

Graphic visualizations can then be developed to characterize the patterns established in the first simulation. These visualizations may not only aid in the research analysis of the traffic patterns, but can also serve as a basis for operational traffic manager displays.

Once the nature of the air traffic patterns has been established, then the nature of complex air traffic situations in the environment can be analyzed, in terms of the complexity and probabilistic nature of the environment.

In parallel with this work would be the development of visual representations of the predictive characteristics of airspace situations.

Having established these environmental foundations, then the fundamental human resource question can be answered: "which tasks *must* be performed by people?" Once the core tasks are established, the supporting tasks can also be defined.

After defining the human tasks in the ATM function, issues regarding human cognitive capacities need to be resolved: how fast, how much, what complexity can a human handle. For control purposes, this may best be done by abstracting the significant features from the operational tasks for evaluation in a simulated environment. The fidelity of this environment to the real-world could then be progressively increased. Increasing fidelity may include expanding the environment to examine group dynamics.

Finally, the ATM functions human operational environment will need to be combined with the simulated airspace environment and the flight specific functions into a high fidelity operational test environment for final simulation testing.

6.2.3 Follow-On

Based on the general research approach, research questions, and descriptions provided in this report, a detailed research plan should be established for completing a human factor analysis of the traffic manager's role.

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