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THE ANALYSIS OF EXPERT PERFORMANCE IN THE REDESIGN  
OF THE EN ROUTE AIR TRAFFIC CONTROL CURRICULUM

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ABSTRACT

This paper describes a cognitive task analysis performed within an integrated framework to analyze knowledge structures, mental models, skills, and strategies of the en route controllers to provide an understanding of the key cognitive components of the controller's job. Seven different procedures were used to collect cognitive data, and the presentation concentrates on the results of three of those procedures as they contributed to an understanding of controller expertise. The procedures under discussion include performance modeling, structured problem solving, and paper problem solving. The performance modeling resulted in the identification of twelve primary tasks and a mental model made up of eight panels that underlie expert controller's organization of domain knowledge. The structured problem solving involved protocol analysis that resulted in the identification of three categories of controller strategies, and the paper problem solving resulted in a hierarchy of goals and a set of methods used by experts to achieve those goals. These results were integrated into a model of the expert controller that will be used specify the instructional content and sequencing for the new curriculum.

**INTRODUCTION**

A cognitive task analysis was conducted as part of the Federal Aviation Administration's redesign of their en route air traffic controller curriculum. This two phase effort was conducted within an integrated framework to analyze knowledge structures, mental models, skills, and strategies of the en route controllers. The first phase included the development of a preliminary mental model with its associated tasks and cognitive strategies. In the second phase, the model was validated, and the tasks and strategies were extended to include a greater portion of the controller's job. The main objective was to provide a detailed understanding of the cognitive components of key controller functions in order to improve controller timing.

This analysis applied some of the procedures of the integrated task analysis methodology (Ryder & Redding, 1990) involving several iterations of data collection, analysis, and interpretation. This effort is an example of cognitive task analyses now being applied to complex, real-time, multiple task environments which involve a high degree of cognitive processing on the part of the operator or analyst. This is in contrast to earlier analyses which concentrated on sequential tasks such as text editing where the task demands and user interface were not as complex. This current effort concentrates on the development of a more robust use mental model and its integration with tasks and cognitive strategies.

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## METHODS

The cognitive task analysis was performed on data gathered from four groups of participants: supervisory experts, intermediates, and novices. The supervisors/experts were Full Performance Level (FPL) controllers with more than 4 years of FPL experience. The intermediates had less than 1 year of FPL experience, and the novices were developmentals who were still being trained. The procedures under discussion include performance modeling with COGNET (Zachary, Ryder, & Zubritzky (1989), protocol analysis of structured problem solving data are the development of Systematic Grammar Networks (Johnson & Johnson, 1987), and paper problem solving based on the paired problem solving technique of Means and Gott (1988).

Performance Modeling: This effort was aimed at constructing a COGNET model of expert controller skill. The basic data for the COGNET modeling was real-time performance of five FPL controllers on four different problem scenarios. Individual DYSIM performance on each problem was videotaped as the participants worked uninterrupted. In a subsequent session, each problem was replayed with the participant, and a verbal protocol obtained to determine why they did each group of actions, what their goals were, how they were making decisions, what goals the actions were part of, etc. Based on this analysis, a preliminary mental model, task decomposition, and individual task models were constructed.

The preliminary COGNET model was extended and refined by having two additional FPLs view a subset of the videotapes of the original DYSIM problems, critique them, and answer questions about alternative methods for handling the same problems and about general methods and strategies for handling a sector.

Developing the COGNET model involved three analytical processes -- decomposing the videotaped problems into a set of tasks, modeling the global problem representation (the mental model), and modeling the individual tasks to the subgoal level. COGNET model development is essentially an iterative process of refinement, in which each iteration provides greater detail, corrections of model components based on incomplete understanding, and refinement for consistency and conformity among parts and links between parts. The observable aspects of the model (behavioral) can be determined in early iterations because they are explicit in the videotapes of controller actions. The cognitive aspects of the models must be added in subsequent iterations, because they must be derived from the protocols and inferred from interviews with SMEs. The specific steps in the analysis process can be found in Redding et al. (1990).

Structured Problem Solving: The structured problem solving analysis involved two iterations. During the first iteration, expert, intermediate, and novice protocols were

analyzed to identify controller strategies under 65% complexity or workload. In the second iteration, that set of strategies was extended by analyzing expert protocols under 125% workload.

In both iterations, the participants solved DYSIM structured problems. These were realistic air traffic control problems presented in a simulated environment with ghost pilots and ghost controllers simulating adjoining sectors. The participants were given some familiarization with Aero Center, and were then asked to work the problems at the DYSIM. They were recorded by video cameras and in the first iteration were prompted by the experimenter to describe what they were thinking about. The audio track from these video tapes was the source of the selective notations, the data that was coded and analyzed.

In the second iteration, under conditions of heavy workload, the participant worked through the entire 20 minute problem. Then the problem was replayed, and the participant was asked to continually talk about the situation in order to determine how controllers make decisions. The participant was asked to discuss the control actions he made, and, most importantly, why he decided on that action. There were six freeze points during the playback, and the participant was asked to describe what happens over the next minute in the section by giving the important information on the aircraft, the part of the plan being executed, and the specific tasks and strategies employed.

The controller protocols were transcribed using the selective notation procedure described in Redding et al. (1990). Each statement was then coded using a coding scheme that included 40 categories of cognitive strategies. The coding scheme is an extension of the strategies identified in the first phase of the research

Paper Problem Solving: In the first iteration of the paper problem solving, paired problem solving data was used to develop a listing of goals and means priorities. That was expanded into an algorithm to account for the relationships between the aircraft and sector information, the prioritization rules, and the calculation required to convert information for prioritization. In the second iteration, training materials were developed for that algorithm, and were presented to participants prior to their solving paper control problems.

Participants from the supervisor and expert controller groups were asked to solve two paper problems. Intermediate and novice groups were presented with the prioritization algorithm and were then asked to solve the same two problems. One problem was a low structure problem made up of several independent situations that required immediate attention. The other problem was a high structure problem involving a few complex situations requiring less immediacy compared with the low structure problem.

The solution sequence predicted by the algorithm was compared against each individual solution sequence, and decision process factors were compared across the four experience groups.

## RESULTS

Performance Modeling: This effort resulted in the

development of an integrated cognitive model (using the COGNET methodology) of expert en route air traffic control prioritization decision making. The component of the model include:

A Mental Mode] -- a conceptual framework for organizing and applying ATC knowledge.

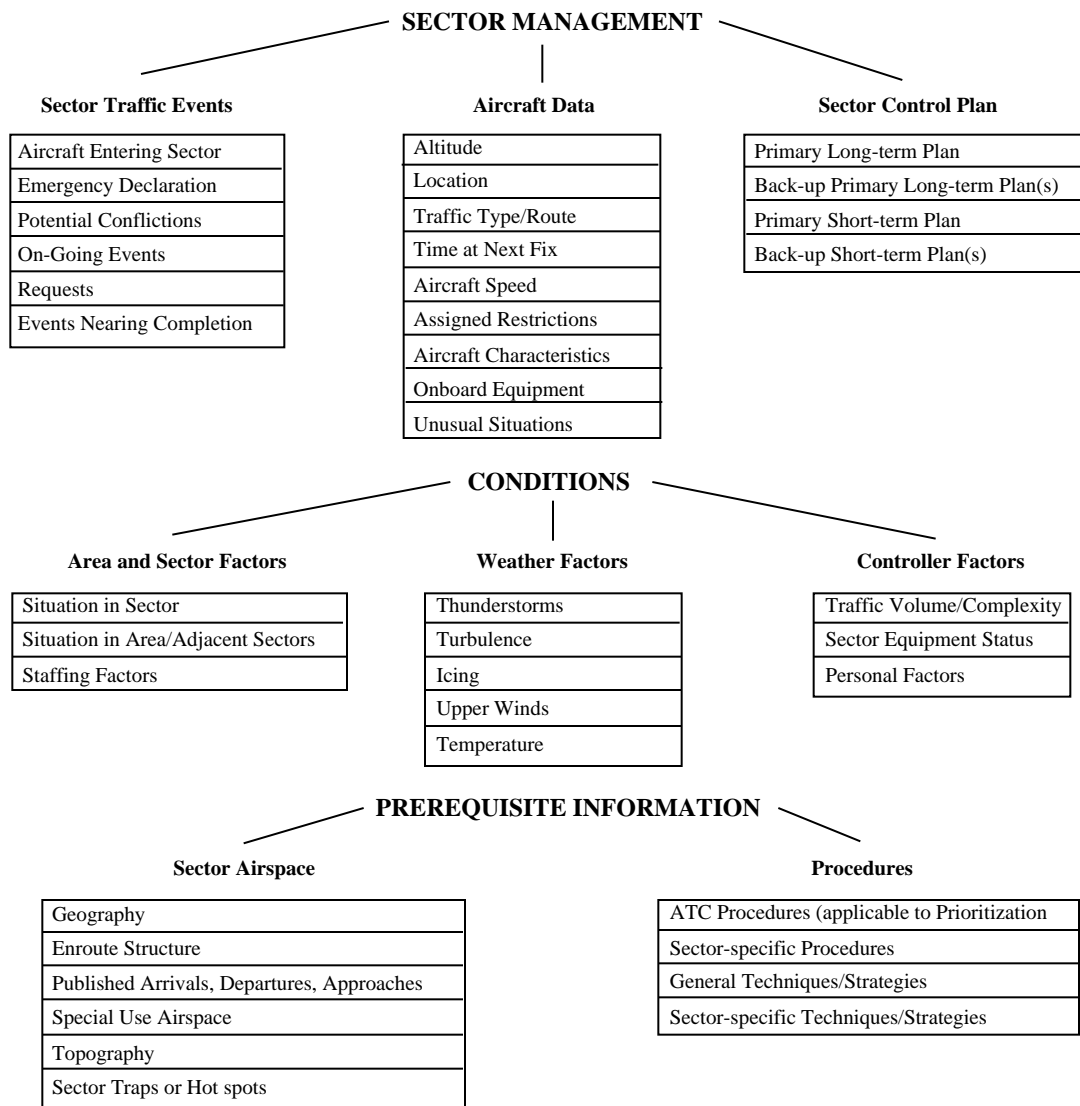


Figure 1. Mental Model of Expert En Route Air Traffic controllers

- A set of 12 Task Models -- each task is a unit of goal-directed behavioral and cognitive subgoals (and implied operations) that contributes to maintaining the safe, orderly, and expeditious flow of air traffic.
- A list of Perceptual Processes -- visual and auditory events that provide direct input about situational changes to the Mental Model as they occur, independent of the task in progress.

These results concentrate on the details of the Mental Model shown in Figure 1. The organization of the

Mental Model, with eight panels clustered into three major categories, depicts the types of knowledge needed to support ATC performance and implies a strategy for applying that knowledge. Its contents at any particular time represent the controller's situational awareness.

The Sector Management panels contain information about the aircraft approaching or in the sector (Aircraft Data), the events that these aircraft are a part of (Sector Traffic events), and the control plan and actions that the controller is planning to use to separate these aircraft (Sector Control

Plan). The panels in the Conditions category instantiate conditions or factors that change a controller's "usual" strategy, resulting in potential increase in actual or perceived workload. They include conditions of runways, airports, equipment, etc. in the sector or adjacent sectors (Area and Sector Factors), various weather conditions that impact traffic control

(Weather Factors), and subjective factors that determine the controller's general level of stress and workload (controller Factors). Taken together, the Prerequisite Information panels contain the knowledge of the "physical" structure of the sector (Sector Airspace) and the procedures by which control is carried out (Procedures).

The Sector Management Category can be thought of as the dynamic knowledge of the sector situation, and the Conditions Category contains factors that influence general workload and selection of specific strategies for handling events. These two categories contain information relating to the situation in a specific sector at a particular time, while the Prerequisite Information Category contains knowledge of the sector and air traffic control procedures, strategies, and techniques that have been learned and committed to long-term memory

The organization of the Sector Management Category implies a specific decision-making *information flow*. The controller perceives data from the PVD, flight progress strips, and from communication with pilots about individual aircraft (Perceptual Processes), s/he processes these data about individual aircraft and categorizes them into events that must be handled (as part of the Maintain Situation Awareness task). An event is a higher-level construct that involves one or a group of aircraft. The long term plan for controlling the sector is devised to handle events (represented as the Primary and Backup Long-term Plan levels of the Sector Control Plan panel of the Mental Model) and then is translated into a detailed plan of specific control actions involving individual aircraft (represented as the Primary and Backup Short Term Plan levels of the Sector Control Plan panel of the Mental Model).

This implies is that decision-making involves events rather than individual aircraft. By learning procedures and strategies for event types, the amount of information needed to make decisions can be significantly reduced. The schemas for event types would include pointers or parameters that reference *specific aircraft data, situational conditions*, or other prerequisite knowledge. The dynamic aspects of the Mental Model are assumed to be either in working memory or easily accessible from long-term memory. Experts will have larger chunks, resulting in a greater *effective* working memory capacity. Using this Mental Model *should* enhance organization and chunking for all levels of controllers, with particular benefit to

novices.

The Sector Traffic Event panel is the primary panel used for decision-making about the prioritization for tasks and duties, since it represents the understanding of the events that must be dealt with. However, determining how to deal with each event involves reference to the data on the Aircraft Data panel and the three Conditions panels, and other events on the Sector Traffic Events panel, as well as knowledge of standard and sector-specific procedures and strategies from the Procedures panel. The events are also interpreted with reference to the static spatial representation of the Sector airspace (embodied on the Sector Airspace panel).

**Structured Problem Solving:** The protocol analysis resulted in the identification of three categories of controller strategies: planning strategies, monitoring strategies, and workload management strategies. A comparison of expert, intermediate, and novice strategy usage highlights several trends in these structured problem solving exercises. First, the experts tend to use fewer strategies as compared with intermediates and novices. Second, experts used workload management strategies more frequently than did intermediates and novices. A detailed analysis of the individual strategies used in each of the three categories revealed that the experts use overall fewer strategies, but they use a wider diversity of strategies as compared with intermediates and novices.

To better understand these trends in expert strategy usage, several of the expert and novice coded protocols were reviewed resulting in the finding that experts tend to include more control actions and/or aircraft with each use of a strategy. Therefore, experts are more efficient at controlling a situation by managing more aircraft with each strategy step. It was also apparent that experts have a wider repertoire of strategies that they can call on to help manage specific situations.

**Paper Problem Solving:** The solution sequence results showed that for the decision process factors, the low structure problem resulted in a good match with the algorithm factors, while the high structure problem resulted in solutions that were more varied and differed from those in the algorithm.

A detailed analysis of these results has led to the conclusion that the two paper problems involved ~o different types of planning. The low structure problem with high immediacy, required short term planning on the part of the participants, with time available to respond a major factor in the decision process. The high structure problem allowed for, and demanded, long term planning due to its complexity and lack of time pressure. It was concluded that the long term planning allows controllers to implement more varied strategies, and the role of prioritization is less important. On the other hand, when controllers are working under conditions requiring

immediate attention, they implement a more homogeneous form of short term planning where prioritization is central.

## CONCLUSIONS

Air traffic control expertise involves the mastery of a large amount of knowledge, behavioral (procedural) skills, and cognitive (decision making) skills. The results from these three cognitive analyses combine to present a collective set of training recommendations. Chief among them, training needs to provide the controller with a framework for acquiring, organizing,

and working with domain knowledge, and the Mental Model serves this function.

Currently, a large portion of ATC training is performed as a part of On-The-Job Training (OJT), in which trainees work traffic at increasingly busy sectors while being coached and monitored by an OJT instructor. Knowledge transfer between instructor and trainee is an informal process that varies with the individual instructor. In order to eliminate this variability, the cognitive approach to ATC training will require standardization of teaching practices in which instructors explicitly teach cognitive aspects of ATC, providing trainees with a richer and more consistent training program.

The Mental Model provides a structure for expert knowledge, and teaching that structure to trainees should expedite the learning and utilization of that knowledge. The structured problem solving results also show the need for a structure in the training of controller cognitive strategies. That analysis resulted in a large number of strategies used by expert controllers to manage a sector. Such a complex set of strategies can overwhelm the trainee unless it is carefully structured. The structure of the Mental Model with its emphasis on sector events provides a way to group strategies so that they can be more quickly learned and more easily accessed during real-time control.

Because the task decomposition in COGNET is goal-based, the tasks correspond to goals rather than the behavioral action sequences in standard task analyses. The Task Models will thus provide the framework for part-task training and teaching by problem types. Delineation of subgoals within the Task Models allows instructors to explicitly teach subgoal recognition. These subgoals also serve as links to the cognitive strategies. This has led to the recommendation that once the strategies have been learned using the Mental Model structure, then trainees should be given practice at the subgoal level to help integrate strategies with the performance of the task. Of the Task Models, Maintain Situation Awareness and Develop and Revise Sector Control Plan, are the two primarily cognitive tasks in which experts are superior to novices, and these tasks should be explicitly trained. For example, the paper problem solving analysis results

indicate that training for the Develop and Revise Sector Control Plan task should emphasize the difference between short-term and long-term planning. Trainees should be taught that short-term planning forces the controller to concentrate only on salient facts needed to separate aircraft; altitude, airspeed, route of flight, and destination. Long-term planning requires a comprehensive awareness of the conditions affecting traffic in the sector, and the Mental Model provides the framework to maintain such a comprehensive situational awareness.

Performance modeling also provides descriptions of the situational conditions that trigger each task model, or Task Triggers. These triggers provide the focus in the training of which tasks to perform at which times. Trainees can thus learn to recognize Task Triggers as they arise and act on them. Implicit in the triggers is the prioritization scheme for task performance. Thus, in learning the Task Triggers, trainees will be learning the situational context for task performance and the decision-making involved in the prioritization of tasks. These results are supported by the paper problem solving which indicate that training should include specific methods for goal prioritization under time-critical conditions. The algorithm supplements the Task Models by providing an explicit prioritization decision-making scheme under short-term conditions, where several tasks are competing simultaneously for attention. Each of the 12 tasks is triggered when particular patterns of information are present in the Mental Model, but neither the Mental Model nor the task triggers specify the temporal priority of simultaneously triggered tasks.

A common theme from the results of these cognitive analyses is the need to include a significant component, "learning to learn," in controller training. This component would include the structure provided by the Mental Model along with methods for acquiring the large body of complex regulations, strategies, and skill required of the expert controller.

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