MITIGATING COMPLEXITY IN AIR TRAFFIC CONTROL: THE ROLE OF STRUCTURE-BASED ABSTRACTIONS

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This report is based on the Doctoral Dissertation of Jonathan M. Histon submitted to the Department of Aeronautics and Astronautics in partial fulfillment of the requirements for the degree of Doctor of Philosophy at the Massachusetts Institute of Technology.

The work presented in this report was also conducted
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By

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ABSTRACT

Cognitive complexity is a limiting factor on the capacity and efficiency of the Air Traffic Control (ATC) system. A multi-faceted cognitive ethnography approach shows that structure, defined as the physical and informational elements that organize and arrange the ATC environment, plays an important role in helping controllers mitigate cognitive complexity. Key influences of structure in the operational environment and on controller cognitive processes are incorporated into a cognitive process model. Controllers are hypothesized to internalize the structural influences in the form of abstractions simplifying their working mental model of the situation. By simplifying their working mental model, these structure-based abstractions reduce cognitive complexity.

Four examples of structure-based abstractions are identified and mechanisms by which they reduce cognitive complexity described. Experimental evidence is presented to support a key cognitive complexity reduction mechanism, the reduction of the “order”, or the degrees-of-freedom, of a controller’s working mental model. The use of structure-based abstractions is dynamic and responsive to changes in task conditions; these changes are hypothesized to reflect transitions between distinct operating modes. Experimental evidence of such changes in the use of standard flows in the airspace is presented.

The cognitive process model and the concept of structure-based abstractions are shown to be useful tools for identifying cognitive complexity considerations arising from changes to the structure of the ATC system. Examples of cognitive complexity considerations for four opportunities to increase the efficiency, capacity, and robustness of the ATC system are presented. The cognitive process model is also used as part of a cognitive review of the current en route controller training system. This review revealed key pedagogical techniques used to teach structure, factors creating the need for sector-specific mental models and abstractions, and opportunities to improve the efficiency of controller training, such as developing more generic airspace.

The results show structure is a significant factor in controller cognitive complexity. Accounting for its impacts is critical for transitioning to future concepts of operations. The cognitive process model and recognition of controller use of structure-based abstractions provide an improved basis for assessing opportunities to improve system performance.

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List of Acronyms

ARTCC	Air Route Traffic Control Center ("Center")
ATC	Air Traffic Control
CTA	Controlled Time-of-Arrival
EMAGE	Enhanced MATLAB Graphics Engine
ETMS	Enhanced Traffic Management System
FAA	Federal Aviation Administration
IFR	Instrument Flight Rules
LOA	Letter of Agreement
NAS	National Airspace System
NRS	National Reference System
OJT	On-the-Job Training
RNP	Required Navigation Performance
RNAV	Area Navigation
SOP	Standard Operating Procedure
STAR	Standard Terminal Arrival Route
SUA	Special Use Airspace
TMU	Traffic Management Unit
TRACON	Terminal Radar Control
URET	User Request Evaluation Tool
VSCS	Voice Switching and Control System
VHF	Very High Frequency
VOR	Very High Frequency Omni-Directional Ranges
VFR	Visual Flight Rules

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CHAPTER 1 Introduction: Cognitive Complexity and the Air Traffic Control System

1.1 Introduction

“Cognitive Complexity,” or the cognitive difficulty of controlling an air traffic situation, is a limiting factor on the Air Traffic Control (ATC) system. In order to protect controllers from situations that are too cognitively complex and, as a result, threaten the safety of the ATC system, constraints are imposed on when and where aircraft can fly. While regulating cognitive complexity, these constraints also limit the capacity and efficiency of the ATC system. Understanding how the design of the ATC system affects cognitive complexity, and how it is managed and mitigated, is an important and timely area of research.

The sources of cognitive complexity are imperfectly understood. The number of aircraft being controlled is commonly considered to be a key source of cognitive complexity; numerous studies have shown a correlation between the number of aircraft controlled and controller errors (Shapiro and Murphy, 2007; Wickens *et al.*, 1997; Metzger and Parasuraman, 2001). However, the number of aircraft controlled is a crude and often unsatisfactory metric (Sridhar *et al.*, 1998); other factors can both create and mitigate the cognitive complexity experienced by a controller.

Based on the research presented in this thesis, the structure of the ATC system is an important factor in controller cognitive complexity. For the purposes of this thesis, structure is defined as the physical and information elements that organize and arrange the ATC environment. Structure encompasses both physical objects, such as radio beacons, as well as information objects such as standard operating procedures and sector boundaries. Structure shapes the air traffic controller’s task and the cognitive strategies and mental models used to perform that task. The structure is a result of engineering decisions such as defining standardized routes or developing arrival procedures; understanding how structure affects cognitive complexity helps ensure that such engineering decisions do not have unanticipated consequences for the complexity reducing strategies used by controllers.

1.2 Problem Statement and Scope of Research

This thesis examines the impact of structure on the cognitive complexity of performing ATC tasks. Using a multi-faceted approach, the relationship between the underlying structure of the ATC system, controller cognitive strategies, and controller cognitive complexity is examined.

1.2.1 Scope: Focusing on Cognitive Complexity

The focus of the research in this thesis is cognitive complexity, a concept distinct from other common uses of the term "complexity." Figure 1–1 presents a simplified model of the ATC process. In the model, the air traffic controller receives information about the current state of an air traffic situation. Based on those surveilled states and a working mental model of the situation and system being controlled, the controller generates commands that influence how that air traffic situation evolves.

In the model, three uses of the term "complexity" can be distinguished: cognitive complexity, perceived complexity, and situation complexity.

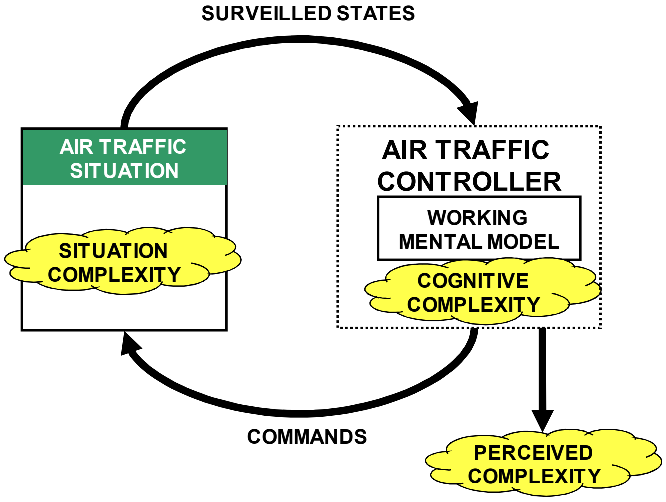

Figure 1–1. Simple model of the ATC process and uses of the term "complexity".

<u>Cognitive Complexity</u>

For the purposes of this thesis, cognitive complexity is understood to be the complexity of the working mental model(s) used by a controller to control an air traffic situation. The controller's working mental model must be of sufficient fidelity to perform the current tasks at an acceptable level of performance. Many different factors will influence the working mental model, and hence the cognitive complexity including the controller's task, their mental models and strategies, as well as factors such as fatigue and stress.

Perceived Complexity

Cognitive complexity is closely related to, but distinct from, the controller's perceived complexity. As shown in Figure 1–1, the perceived complexity is the externalization of the controller's self-reported, or internal perception, of the cognitive complexity. There are multiple methods for sampling perceived complexity; for example, on asking a controller "how complex is this traffic situation?," a controller's verbal report of how complex it appeared to him or her is an example of perceived complexity.

Probing and using reports of perceived complexity can be a valuable research method and has been widely used as the standard in the calibration of metrics of complexity (Laudeman *et al.*, 1998; Kopardekar and Magyarits, 2003). However, differences between the perceived complexity and the actual cognitive complexity are important. A controller may be unaware of the cognitive processes he or she is using; for example, experienced controllers, familiar with a region of airspace, may not always be aware of the strategies and simplifications they are using.

Situation Complexity

Situation complexity is a third distinct use of the term "complexity." Situation complexity refers to uses of the term "complexity" as an objective and measurable property of the system being controlled. Metrics of complexity based on properties or characteristics of the situation are examples of measures of situation complexity. Much of the previous research on complexity in ATC has been focused on the development of metrics of situation complexity that can be used as predictors of the need for imposing traffic management constraints on the ATC system (Laudeman *et al.*, 1998; Sridhar *et al.*, 1998; Hilburn 2004).

While related, situation complexity and cognitive complexity are not equivalent. Situation complexity acts as a source of cognitive complexity. However, a controller's mental models and strategies are key factors that affect the cognitive complexity experienced by a controller due to a particular configuration of aircraft.

Cognitive complexity is the use of complexity most closely related to the decision making processes that are important determiners of the safety and efficiency of the ATC system. Therefore, the scope of this thesis focused on developing a deeper understanding of how structure affects cognitive complexity. The primary area of interest was understanding how structure influences controller strategies and working mental models. The thesis concludes with two examples demonstrating how the results of the analysis can be applied.

1.2.2 Scope: Focusing on Radar Surveillance Environments

The scope of the research presented in this thesis was also constrained to radar surveillance ATC environments. Air traffic controllers operate in a variety of task environments. In the context of Figure 1–1, two key sources of differences in these environments are the surveillance information available to the controller and the types of commands. The types of decisions and working mental models used by controllers working in primarily visual environments are distinct from those used in radar surveillance environments near and between airports.

This thesis focuses on radar surveillance environments (e.g. terminal and en route control). Handling more than 80,000 flights a day, terminal and en route controllers have significant impacts on the efficiency of aircraft trajectories and capacity of the system; in addition, there are significant opportunities in these environments to improve operational performance.

1.3 Motivation

The potential consequences of mistakes by controllers due to excessive cognitive complexity make it critical to ensure the cognitive complexity limits of controllers are respected. This is particularly true when fundamental changes to the design of the system being controlled are being considered; changes may undermine techniques and strategies that help controllers regulate and mitigate their cognitive complexity. It is important, therefore, to understand the factors that impact cognitive complexity and controllers' decision-making processes, and especially how cognitive complexity is mitigated. Such an understanding can also help guide changes to the system in order to promote efficiency while retaining support for cognitive complexity reduction strategies.

Current practices to limit cognitive complexity create inefficiencies and reduce the flexibility of aircraft operators. Limiting the number of aircraft a controller is responsible for forces aircraft to be delayed or re-routed, adding costs to the users of the ATC system. Aircraft trajectories are constrained in both space (e.g. required routes) and time (e.g. delayed takeoff times) in order to regulate and manage both the inputs into the air traffic situation as well as the dynamics of aircraft within the situation. In the absence of these constraints, the volume of aircraft as well as requests for specific trajectories, altitudes, and deviations could create situations that overwhelm a controller's ability to manage safely the resulting cognitive complexity (Metzger and Parasuraman, 2001).

The structure of the ATC system is one of the techniques used to introduce constraints and hence has significant impacts on the efficiency of aircraft trajectories and other aspects of performance.

These constraints on aircraft trajectories can force aircraft to fly non wind-optimal routes and at altitudes that are not fuel-optimal. A fixed-route structure is also rigid and unresponsive to variations in the ATC operational environment such as the position of the jet stream, turbulence, convective weather, and military or other special use airspace operations; in many cases this rigidity leads to inefficient and suboptimal fuel burn and cost. Fuel costs and environmental concerns are only increasing the push for more efficient operations.

1.4 Applications of Research

The results of examining the impacts of structure on cognitive complexity are relevant to a range of applications. Three key applications are:

- improving airspace design and ATC system performance,
- identifying cognitive complexity considerations of new technologies, procedures, and concepts of operations, and
- improving metrics of complexity used for traffic management.

Airspace design has been rated second only to traffic volume as a source of complexity (Kirwan *et al.*, 2001). Identifying important elements of structure supports the design of simpler airspace that can increase capacity and throughput. Such insight can also identify opportunities to reduce costs to airspace users without inducing unanticipated consequences on controller cognitive complexity. For example, expanded use of new aircraft navigation capabilities such as Required Navigation Performance (RNP) standards and Area Navigation (RNAV) creates opportunities to consider a novel and more efficient route structure. Understanding structure's impact on cognitive complexity can help ensure that those opportunities respect controller cognitive complexity limits.

Existing constraints and associated costs are prompting the development of new operational concepts, tools, and procedures that are capable of handling forecast increases in demand for air travel (RTCA, 1995; Wickens *et al.*, 1997; Metzger and Parasuraman, 2001). In addition, new aircraft technologies such as Very Light Jets (VLJs) are enabling new forms of operations such as on-demand air taxi services that may not fit typical operating patterns. The introduction of new technologies, procedures or operational concepts will likely shift and alter the role of controllers and modify their tasks. Understanding how structure in the current ATC task environment impacts cognitive complexity provides a basis for assessing complexity issues in future concepts of operations and evaluating design trade-offs and operational considerations.

Finally, understanding the impact of structure on cognitive complexity provides a basis for more accurate situation complexity metrics. Current operational metrics of complexity “do not adequately represent the level of difficulty experienced by the controllers under different traffic conditions” (Sridhar *et al.*, 1998). Improved metrics would support better traffic management decision support tools; more accurate prediction of controller overload conditions would enable earlier and less disruptive implementation of traffic management restrictions. While an important and promising area of research (Li *et al.*, 2008), the development of improved metrics is not specifically addressed in this thesis.

1.5 Objectives of the Research

The objectives of this research are to

Objective 1: Identify key factors influencing controller cognitive complexity.

Objective 2: Identify core elements of structure in the operational environment.

Objective 3: Develop a hypothesis of the mechanisms by which this structure impacts controller cognitive complexity

Objective 4: Evaluate key aspects of one of these mechanisms using empirical methods

Objective 5: Demonstrate how an understanding of these mechanisms can be used to identify cognitive complexity considerations in future ATC systems and potential improvements to controller training.

In order to achieve these objectives, a human-centered systems engineering approach was used; the approach focused on understanding both the cognitive capabilities and limitations of the human while also examining the context of the operational ATC system. A combination of observational, experimental, and analytic methods were employed to investigate the ATC operational environment and controller working mental models. Based on the results, a cognitive process model is developed incorporating key influences of structure on cognitive complexity. The thesis concludes with two examples illustrating applications of the cognitive process model.

CHAPTER 2 Complexity And Cognition

Interest in complexity in Air Traffic Control (ATC) can be traced back to the early 1960s and early work investigating the maximum number of aircraft that can be safely controlled in a sector (Davis *et al.*, 1963; Arad, 1964). This chapter summarizes definitions of complexity and the previous research on complexity in ATC. Key cognitive processes used by controllers to perform the ATC task are reviewed in the context of a synthesized cognitive process model.

2.1 Definitions of "Complexity"

"Complexity" is an often nebulous term, seemingly intuitive yet difficult to define precisely. Formally, complexity is defined as "hard to separate, analyze, or solve…" (Mish, 2008), consistent with most people's general understanding of the term (Hilburn, 2004).[1] Specifying what makes something "difficult", "hard" or "complex" is challenging; however, there are several characteristics that are common to definitions and common uses of the term complexity. This section introduces three key characteristics of the concept of complexity that are prevalent in previous definitions of complexity.

A comprehensive analysis of complexity across multiple domains showed that many definitions have the characteristic of capturing the "size", "count" or "number of" items in an object (Edmonds, 1999). The number of lines of code contained in a computer program, for example, is a common measure of the program's complexity. However, as Edmonds (1999) points out, size seems to highlight a potential for complexity, but may not be sufficient to account for the full richness of what is meant by complexity.

A second key characteristic of definitions of complexity is its association with objects, concepts, or problems "composed of interconnected parts" (Flexner, 1980). The notion of "interconnections" is indicative of the importance of the relationships between the constituent

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[1] Page (1998) offered a distinction between complex and difficult problems: difficult problems have large state spaces with non-linear relationships amongst the variables; complex problems have similar states spaces, except the relationships themselves are dynamic and depend on the actions of decision makers or other agents. Within the ATC literature, the distinction between difficulty and complexity has not been drawn and they will be used synonymously in this thesis.

parts of a situation or problem. The presence of dependencies between parts appears to be a necessary condition for complexity to arise; something easily decomposed into non-interacting components is generally not considered complex. Xing and Manning (2005) has proposed that complexity be understood as a multidimensional construct with attributes encompassing the number and variety of elements as well as the relations between them.

The third key characteristic is that complexity depends on how the object or problem is represented. Representations determine what is considered the parts of the object or problem and the resulting relationships. Representing the same object or problem in two different ways can significantly change complexity. The choice of representations is often a consequence of the task. For example, the complexity of a pile of nails is very different depending on whether one is searching for something to hang a picture on, or trying to model the forces helping it retain its shape.

The last two key characteristics are reflected in Edmonds (1999) working definition of complexity:

> *That property of a language expression which makes it difficult to formulate its overall behavior, even when given almost complete information about its atomic components and their inter-relations.*

This is analogous to the complexity of producing a proof in mathematics. Even given all the formal rules and axioms of mathematics, the production of a proof can be a very difficult cognitive task. This definition captures an essential notion of cognitive complexity of many ATC tasks: in spite of the availability of almost complete information about where aircraft currently are (e.g. through a radar situational display) and where aircraft are expected to go (e.g. through flight strips), formulating accurate expectations of the evolution of an air traffic situation is very difficult.

2.1.1 Complexity Definitions Used in ATC Domain

The three key characteristics of complexity are consistent with typical uses of the term complexity in the ATC literature; however, formal definitions of complexity are relatively infrequent in the ATC literature (Hilburn, 2004). Complexity is often defined as a driver of workload and as something imposed on a controller (e.g. Hilburn, 2004, Mogford *et al.*, 1995). Grossberg (1989) defined complexity as “a construct, referring to the characteristics, dynamic and static, affecting the rate at which workload increases."; similarly, Athènes *et al.* (2002) describe complexity as “a way to characterize air situations” and as a source of workload.

Similar to Grossberg (1989), many definitions identify the underlying characteristics of the task environment as important sources of complexity; Mogford *et al.* (1995) define complexity as "a multidimensional concept that includes static sector characteristics and dynamic traffic patterns." Meckiff *et al.* 1998, recognize that the "operational procedures and practices" as well as the "characteristics and behavior of individual controllers" play a key role.

In many cases it appears that authors presume that there is a shared understanding in the research community of what complexity is. However, it is not always clear whether complexity is being presumed to be an intrinsic property of the configuration of traffic (situation complexity), a subjective experience of the controller (perceived complexity), or a property of the processes being used to perform the ATC task (cognitive complexity).

2.1.2 Complexity in Other Domains

Complexity as a term is of interest in many other domains. Within the literature on psychology research, cognitive complexity is used as an adjective, describing a person's psychological make-up or personality (Bieri, 1961). An individual that uses a large number of internal constructs to perceive and reason about the world has high cognitive complexity (Schneier, 1979). A second use is as a reference to a "theory for studying humans as information processors" (Green, 1997). The cognitive complexity of an individual will reflect their capabilities to differentiate, or break information into smaller units, and integrate, or combine units of information into a larger whole (Green, 1997).

Formal definitions of computational complexity are common in the computer science literature. Minimizing the number of elements used to represent or generate an object or concept is often associated with complexity. For example, Kolmogorov complexity is a measure of the shortest computer program (algorithm) that can produce a given string. Algorithmic information complexity is a measure of the shortest program required to produce a particular output (Edmonds, 1999). For a given algorithm, algorithm complexity analysis can express complexity both in terms of the minimum number of steps required, and/or the minimum amount of memory, or space, required, to compute a solution to the problem. (Halford *et al.* 1998, Pg. 46).

Cyclomatic complexity is a complexity metric that attempts to capture the dependencies between components. It considers the number of linearly independent loops through a system, with the assumption that the greater the number of feedback loops, the greater the potential for complex behavior (Vikal, 2000). Vikal (2000) has used cyclomatic complexity to analyze the apparent complexity of a flight management system to a pilot.

2.2 Complexity Factors and Metrics in Air Traffic Control

Despite the lack of formal definitions of complexity in ATC, significant research effort has been expended identifying complexity factors and capturing them within operational metrics of complexity.

2.2.1 Complexity Factors

There have been several significant efforts to develop lists of complexity factors (for reviews see Hilburn, 2004; Majumdar and Ochieng, 2001). Typical complexity factors identified include: the density of aircraft, the proportion of aircraft changing altitudes, and points of closest approach. Relevant characteristics of the underlying sector that are often identified include sector size, sector shape, and the configuration of airways within the sector. The Wyndemere Corporation (1996) identified several factors associated with underlying structure, such as the importance of special use airspace, the proximity of conflicts to sector boundaries, and the number of facilities the controller must interact and coordinate with. Kopardekar and Magyarits (2003) found significant differences in the relative importance of complexity factors between en route facilities in the United States.

A variety of techniques have been used to elicit complexity factors. Direct techniques use the results of verbal reports, questionnaires, and interviews to elicit complexity factors Mogford *et al.* (1994a, 1994b). Kopardekar *et al.* (2007) describe collecting complexity ratings from controllers actively controlling a simulated sector. Indirect techniques use statistical techniques analyzing controller judgments of the relative complexity of different air traffic situations to determine potential complexity factors Mogford *et al.* (1994a, 1994b). Structured interviews (Wyndemere, 1996), and complexity factor rankings (Mogford *et al.,* 1994b) have also been used.

Factors may be used both as sources of complexity, and as indicators of complexity (Schmidt, 1976). For example, some controller tasks such as communication, data entry, or coordination activities are cited both as activities contributing to complexity, or complexity factors, and used as complexity indicators through the direct measures of these activities (Manning *et al.*, 2000). In other cases, complexity factors are unintended consequences of interventions intended to reduce cognitive complexity. In discussing a proposed “complexity chain” of interventions mitigating “environmental complexity,” Cummings *et al.* (2005) identify “organizational” and “display” factors as interventions that can inadvertently increase a controller’s cognitive complexity.

2.2.2 Early Complexity Metrics in Air Traffic Control

Complexity factors form the basis for metrics of situation complexity. The earliest efforts towards situation complexity metrics appear to be the work performed by (Davis *et al.*, 1963) and (Arad, 1964). Jolitz (1965) found that the number of aircraft handled, N, predicted controller judgments of their workload better than the models proposed by Arad. Since then, multiple efforts have attempted to improve upon the basic aircraft count approach, including Schmidt's (1976) proposal of a Control Difficulty Index (CDI), based on an analysis of event frequency and difficulty.

2.2.3 Dynamic Density Metrics and Free Flight

Renewed interest in metrics of complexity was triggered by the concept of dynamic density introduced as part of efforts towards "Free Flight" in the mid 1990's. Conceptually, dynamic density was introduced as a way of defining situations that were complex enough that centralized control would still be required (RTCA, 1995). Multiple metrics of dynamic density have been proposed (Smith *et al.*, 1998; Laudeman *et al.*, 1998; Wyndemere, 1996; Chatterji and Sridhar, 2001). Some results indicated that a unified version of the various dynamic density metrics may perform better than simple aircraft count (Kopardekar and Magyarits, 2003). However, the Monitor Alert Parameter (MAP) metric used for predictive traffic flow management in the current operational environment still relies on aircraft count.

A number of efforts have used variations on aircraft count such as modifying the count by the average flight time for an aircraft through a sector (Buckley *et al.*, 1969; Mills, 1998). Other metrics that are currently in operational use are based on traffic densities and sector transit times; this includes the Nav Canada PACE model (Stager *et al.*, 2000). The effects of clusters, regions of locally high traffic density in a sector that has low overall traffic density, have been analyzed by Aigoin (2001).

2.2.4 Structure in Complexity Metrics

Most of the terms in the metrics that have been proposed have reflected "geometrical factors" such as points of closest approach between aircraft, variations in the headings of aircraft, and aircraft densities. However, the underlying airspace structure has not featured prominently in many of the proposed metrics. Two air traffic situations may have an identical dynamic density value, but may not be of the same cognitive complexity due to cognitive simplifications provided by the structure in one of the situations.

There are a small number of examples of structure being captured in complexity metrics. Wyndemere (1996) proposed a metric that explicitly included a term capturing “airspace structure.” This term computes the correspondence between aircraft headings and an identified “long axis” of a sector. Aircraft crossing the “long axis” or going “against the grain” are weighted to be significantly more complex than those that are “going with the flow.”

Some metrics may implicitly capture some of the effects of structure. Delahaye and Puechmorel (2000) have examined measures of topological entropy as a means of quantifying the complexity of a traffic situation. The aircraft within a sector are modeled as elements of a dynamical system for which the Kolmogorov entropy can be computed. A high entropy value is associated with significant disorder in the trajectories, or lack of structure, which is interpreted as indicating a high level of complexity in the system.

Despite this lack of inclusion in metrics, the airspace structure is considered an important factor for understanding complexity. Airspace design has been rated second only to traffic volume as a source of complexity (Kirwan *et al.*, 2001). As Sridhar *et al.* (1998) note, the “current measure represents only the traffic flow conditions and could be improved by incorporating effects of structural characteristics like airway intersections, as well as other dynamic flow events such as weather.”

2.3 Cognitive Processes

Understanding the cognitive processes used to perform the ATC task is challenging. Cognitive processes are not directly observable and must be inferred from operator behavior; there can be significant differences between individuals, the processes are dynamic, and behaviors vary in time (Rouse, 1980). Additionally, the products of the operators cognitive processes will not necessarily be unique for a given input, nor optimal; humans often satisfice the task conditions rather than optimize (Simon, 1990).

Despite these challenges there appears to be a consensus that certain key processes are useful for describing how humans think about and make decisions with respect to controlling dynamic environments, like ATC. Understanding the capabilities and limitations of these processes is important for understanding the sources of cognitive complexity. As pointed out by Simon (1990) “basic physiological constants determine what kinds of computations are feasible in a given kind of task situation and how rapidly they can be carried out.”

2.3.1 Previous Cognitive Models

Multiple models of cognitive processes have been developed, including several specific to air traffic controllers. Hilburn (2004) reviews many of the models that have been proposed by researchers including analogies of the human as a failure detection system (Gai and Curry, 1976), and as a time-shared computer (Schmidt, 1976). Other modeling approaches have attempted to build representative simulations of human behavior based on low-level information processing and decision making. Extensive and detailed fast-time simulation models of controller processing, such as the Man-Machine Integration, Design, and Analysis System (MIDAS) model developed by Corker *et al.* (1997), have been used to investigate new procedures and operating paradigms such as delegating separation responsibility to pilots.

Information processing models are common approaches to modeling controller cognitive processes (Oprins *et al.*, 2006; Hilburn, 2004). Information processing models, such as that described by Wickens and Hollands (2000), consider the flow of information into and through a controller's cognitive processes and how the outputs from a human feedback and affect the system being observed or controlled. Endsley's (1995) model of situation awareness, shown in Figure 2–1 is an example of the common decomposition into awareness, decision-making, and action.

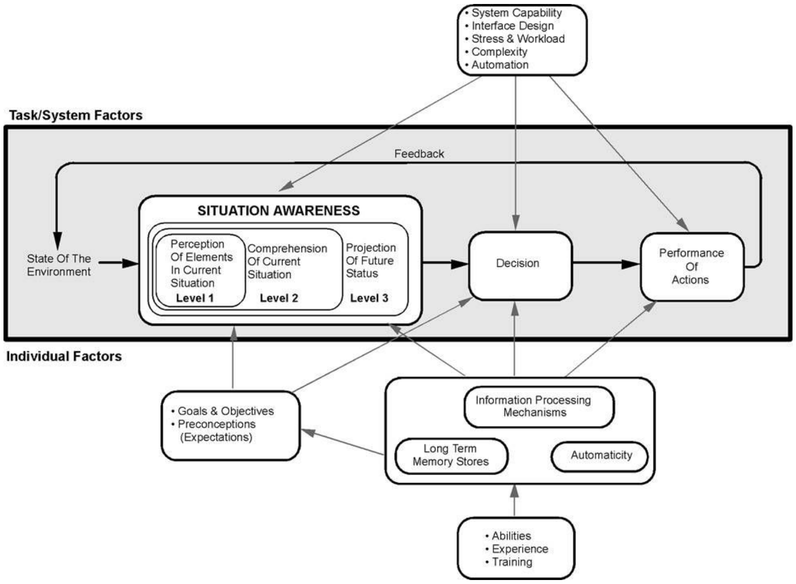

Figure 2–1. Endsley's (1995) model of situation awareness.

2.3.2 Situation Awareness

Endsley (1995) defines situation awareness as comprising three levels: "the perception of elements in the environment, within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future." Examples of Level 1 situation awareness include perceiving the presence of aircraft (computer identifiers, current routes, altitudes etc…), the state of decision support, surveillance, and communication equipment, hearing requests from pilots and other controllers and being aware of current weather conditions impacting the sector. For the controller, Level 2 situation awareness includes comprehending current distances between aircraft, and their awareness of the accuracy of surveilled information such as aircraft positions, airspeeds, and headings. Level 3 situation awareness is awareness of projected future states such as future aircraft positions and the resulting distances between aircraft, changes in weather, and the impacts of potential route changes.

2.3.3 Decision Processes

As shown in Figure 2–2, Pawlak *et al.* (1996) developed a model describing key decision processes used for conflict detection and resolution in ATC. The model encompasses four key types of decisions made by air traffic controllers: planning, implementing, monitoring, and evaluating. Planning involves a controller determining a set of control actions to resolve any conflicts in the situation; implementing is the process of executing those control actions. The situation is monitored to check conformance of the situation against the plan while evaluating verifies the effectiveness of the plan in resolving the conflicts in the situation.

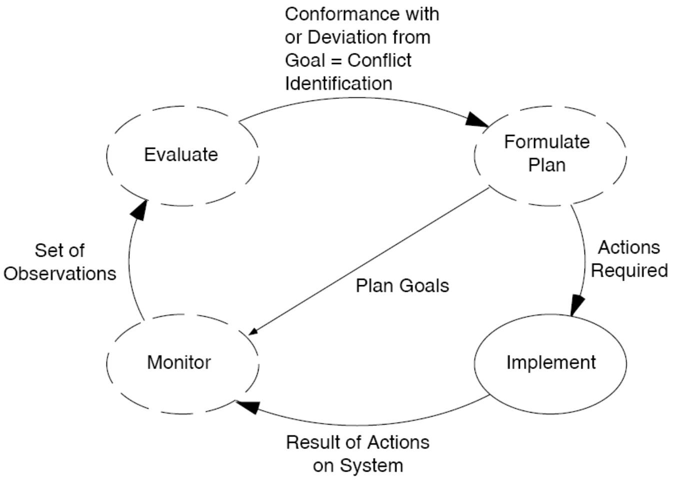

Figure 2–2. Pawlak *et al.'s* (1996) model of decision processes for conflict detection and resolution.

In general, the decisions made by controllers are a product of tradeoffs between accuracy, time available, and cognitive effort required. Early researchers on decision making generally presumed a rational and optimal decision maker and produced normative models. However, such models did not account for the use of strategies and heuristics by humans; nor do they account for the range of different types of decision-making activity.

The realities of real-world decisions have led to development of theories of naturalistic decision-making (Klein, 1989). Studies of decision makers in complex environments from fire fighting to airline cockpits shows a common reliance on recognition processes, or Recognition Primed Decision-making (RPD), that allow decision makers to intuitively solve problems based on perceived clues rather than conscious calculation (Simon, 1990). RPD allows solutions to problems to be recognized rather than developed from first principles. Mogford (1994b) reports controllers described solutions as emerging fully formed, consistent with expert use of RPD processes.

2.3.4 Working Mental Model

Working mental models support the generation and maintenance of situation awareness as well as the various decision-making and implementation processes. Working mental models are a controller's cognitive representation of the system, appropriate for the needs of the current task (Mogford, 1997; Wilson and Rutherford, 1989; Doyle and Ford, 1998; Davison and Hansman, 2003).

Within this thesis, the working mental model is understood as a controller's internal representation of the current states and dynamics of the system being controlled. It is dynamic and adapted to the current task. The working mental model is considerably more fluid and adaptable than static mental models maintained in long-term memory. How working mental models are developed, and the process by which they are selected, is complex, adaptive, and incompletely understood.

2.3.5 Mental Models and Abstractions

Working mental models can draw upon abstractions, or simplified versions of a system's dynamics. Abstractions are a means of representing the essential characteristics of a mental model in a more cognitively compact form that is manageable within the constraints of human memory and processing limitations. As Rasmussen (1986) states, the abstraction process is "not merely removal of details of information on physical or material properties. More fundamentally, information is added on higher level principles governing the cofunction of the various functions or elements at the lower levels."

A notional representation of the abstraction process is presented in Figure 2–3. Before abstraction, detailed mental models can overwhelm a controller's limited attention resources (e.g. restricted to that information included within the attention spotlight). After using an abstraction to simplify part of the mental model (grey boxes to black box), the controller is able to attend to a simplified version of the system the working mental model.

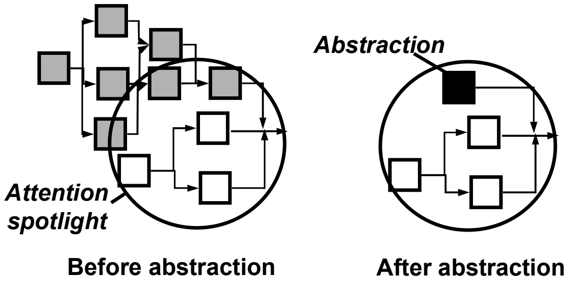

Figure 2–3. Illustration of the abstraction process (from Reynolds *et al.,* 2002).

The working mental model operates at a level of abstraction appropriate for the current cognitive activity. It incorporates the dynamic models used to generate the projections required for the current task. Too low a level of abstraction, or too detailed a representation of the dynamics of the situation, can make the working mental model inefficient. At too high a level of abstraction, detail important for successful performance of the task may be lost.

The use of abstractions reduces the footprint in working memory used to store and maintain representations of the current states of the operational environment. Working memory has been described as a "workbench", that temporarily retains verbal and spatial information; it is one of the key bottlenecks that limit the capacity of controllers to process information (Kalus *et al.*, 1997, Pg. 17). While there is considerable debate around the exact capacity (Cowan, 2001; Halford *et al.*, 1998), there is general consensus that the capacity of working memory is best understood as a limit on the number of chunks that can be retained. Evidence from memory span tasks suggests that is the number of integrated objects, or chunks that limits the capacity; this capacity appears to be independent of the complexity of the individual chunks. (Halford, 2001, Pg. 1). Abstractions provide an important mechanism for limiting the number of chunks and thus reducing the demand on a controller's cognitive resources.

2.4 Complexity Mitigation

Humans are adept at changing strategies and approaches to a task in order to minimize the mismatch between the demands of the task, their cognitive resources, and minimum performance standards (Wickens, *et al.*, 1997). The cognitive complexity experienced by a controller is not an external input over which the controller has no control. Rather, cognitive complexity is a property of the controller's working mental model that reflects the controller's representation of the situation and its dynamics. Thus, there are several mechanisms by which a controller can control and mitigate their cognitive complexity.

Controllers can mitigate and reduce cognitive complexity through changes to how the situation and its dynamics are represented in the working mental model. By changing the level of abstraction the air traffic situation is represented at, simpler dynamics can be used in the working mental model. As suggested by the three key characteristics of complexity identified above, abstractions reducing the number of elements in the working mental model, and the interconnections between them, provide mechanisms by which controllers can reduce and mitigate the cognitive complexity of their task. The ability to represent situations in more compact and less cognitively challenging forms is a key indicator of expertise. As Ellis and McDonell (2003, Pg. 371) state, "the way in which individuals represent tasks is regarded as one of the most significant differences between novices and experts."

Changing their mental model allows controllers to adapt their cognitive effort to the minimum performance needs of the task. Davison-Reynolds (2006) introduced a "projection error concept", capturing the tradeoff controller's can make between the cognitive task load of a working mental model and the quality of the resulting projection. Simpler working mental models, reducing cognitive complexity, may sacrifice projection quality that may not be necessary for performing the current task.

In addition, the recognition primed decision making strategies discussed above provide cognitively simple ways to identify solutions quickly. Recognition primed decision making can take advantage of abstractions simplifying the working mental model and enabling pattern matching. Experts appear to be able to rely on recognizing patterns in a domain without detailed, careful, and cognitively intensive, consideration of the situation. Expert controllers categorize problems using fewer, but more complex, dimensions than novices; experts appear to have greater insight into the relevant properties of the air traffic situation (Mogford *et al.*, 1994a).

Changes in strategies are an addition means by which controllers can mitigate cognitive complexity. Strategies and techniques are domain or airspace specific approaches to performing a task. A controller's strategies and techniques are developed over time from experience and through training processes. Strategies and techniques help controllers narrow the range of possible command actions. Aircraft can be turned, climbed, sped up, slowed down or complex combinations thereof. In many cases, the trajectory of more than one aircraft could be altered in order to successfully perform the task. Many different strategies for controlling traffic can be used successfully (Cardosi and Murphy, 1995) and the strategies that are appropriate may depend on a variety of external factors including weather and airspace.

A comprehensive cognitive task analysis of controllers showed expert controllers used a greater number of workload management strategies which reduced the number of aircraft they had to attend to (Seamster *et al.*, 1993). These strategies simplified the situation and reduced the monitoring effort of the controller (Seamster *et al.*, 1993). Shifts to more conservative decision making, including using prompt corrective actions at the possibility of a problem, have also been observed (Bisseret, 1981).

Finally, controllers have considerable control over their task environments (Sperandio, 1978; D'Arcy and Della Rocca, 2001; Hilburn, 2004; Wickens, *et al.*, 1997). Information overload is a frequent challenge for controllers (McMillan, 1998, Pg. 20). By slowing their rate of speech and avoiding the condensing of messages, controllers can assert more control over their task environment, freeing time for planning and flight data tasks (McMillan, 1998, Pg. 20). Controllers can also regulate the rate of incoming aircraft, place restrictions on the trajectories of aircraft, and/or modify their tolerance for aircraft non-conforming with standard procedures. Controllers can also shed certain parts of the task, for example through not providing or discontinuing particular services to pilots (Sperandio, 1978; Hopkin, 1995; Bisseret, 1981).

2.5 Chapter Summary

This chapter has reviewed common definitions of complexity used in ATC and other domains. While often associated with "size" or "counts" of objects, these properties are often not sufficient to capture the richness of the term. The relations between objects and how they are represented are important characteristics of complexity.

A review of metrics of situation complexity in ATC shows there appears to be a lack of systematic inclusion of the effects of underlying structure on cognitive complexity. Key cognitive processes, including situation awareness and the use of mental models, were presented.

Abstractions provide powerful simplifications of a controller's working mental model. Changes in strategies, including the use of strategies taking advantage of a controller's ability to manipulate the operational environment, provide additional opportunities for cognitive complexity reduction.

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CHAPTER 3 Radar Surveillance Air Traffic Control

In order to understand how structure impacts cognitive complexity, it is important to understand the ATC task and operational context within which air traffic controllers operate. The simple model presented in Figure 1–1 above was expanded to incorporate key parts of the ATC operational environment (left side of Figure 3–1). The expanded model of the operational environment captures important parts of the “plant” or “system” being controlled, including the controller’s task, as well as sources of information, and command implementation mechanisms.

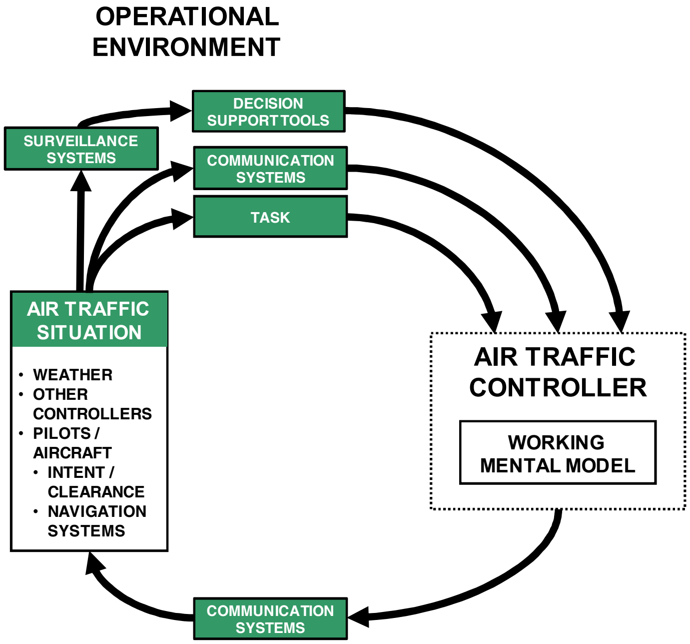

Figure 3–1. **Expanded model of ATC operational environment.**

3.1 Background: Facilities, Sectors, and Sector Teams

Before discussing the operational environment modeled in Figure 3–1 in detail, this section provides background of the different types of facilities, divisions of airspace, and teams controllers operate in.

3.1.1 Facilities

Controllers provide radar control services primarily at Terminal Radar Approach CONtrols (TRACON) and Air Route Traffic Control Centers (ARTCCs). There are 24 ARTCCs in the

United States providing ATC services to enroute aircraft. The airspace of the 20 ARTCCs providing ATC services over the continental United States is shown in Figure 3–2. Controllers working in these Centers provide services to aircraft enroute at cruising altitudes; in addition, they climb and descend aircraft to/from those cruising altitudes, and provide merging, sequencing and initial descent for aircraft with common destinations. The airspace controlled by Centers often overlies sparsely settled regions and controllers can be responsible for aircraft arriving and departing small or uncontrolled airports.

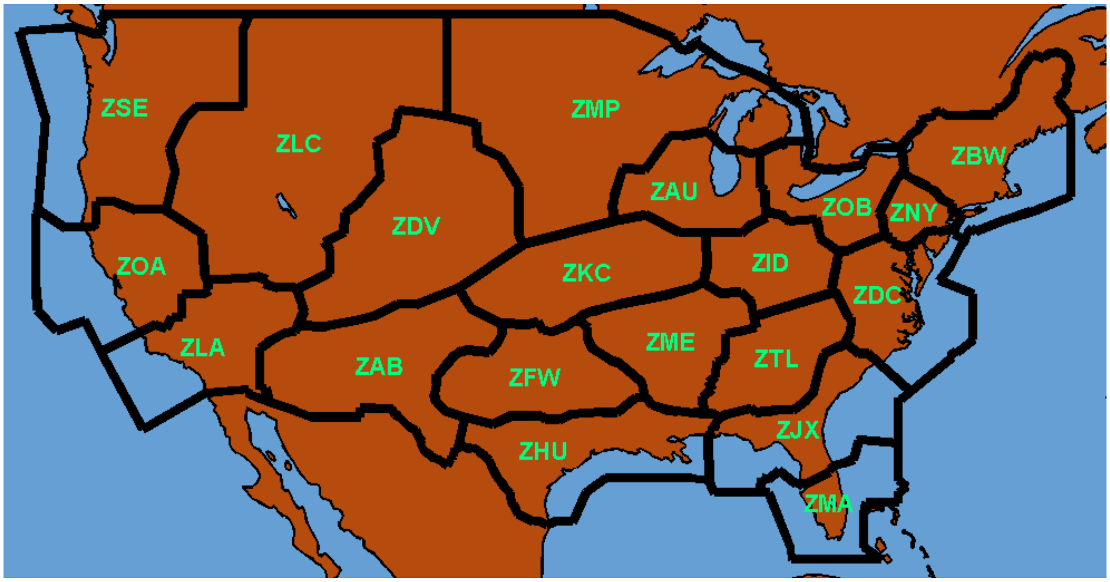

Figure 3–2. Airspace over the continental United States is controlled through 20 ARTCCs.

Near major airports, the airspace is controlled by terminal controllers working in a TRACON. A typical TRACON will control airspace within forty miles of the primary airport at altitudes from the floor of controlled airspace up to 18,000 feet. Controllers in TRACONs provide the final sequencing and merging of aircraft as they progress towards the landing runway. Controllers also provide ATC services to aircraft that have departed the primary airport and are in their initial climb to an enroute altitude.

3.1.2 Airspace Divisions: Sectors

Within United States ATC facilities, airspace is typically divided into discrete areas of responsibility known as sectors.[2] There are more than 750 enroute sectors defined in the United States. Each sector has lateral and vertical boundaries adapted to the local operational needs; this yields a wide range of sector shapes, sizes, and altitude levels.

The three dimensional perspective of a sector between New York and Washington D.C. in Figure 3–3 shows how sector boundaries can vary with altitude and are non-uniform. Sectors often have shelves, or small irregular pieces of airspace added on, or subtracted from a sector. Shelves are typically designed around predominant traffic flows and are used to reduce the number of sector transitions as aircraft proceed through the system.

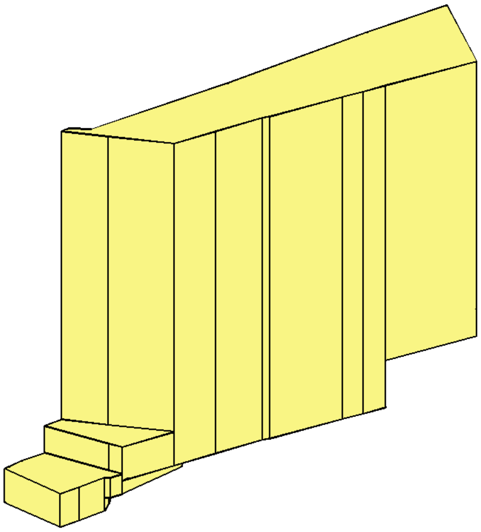

Figure 3–3. Three-dimensional perspective of sector near Washington, D.C.

Sector boundaries are generally static. However, within a TRACON, and for nearby sectors in an ARTCC, the specific configuration of airspace often depends on the runways in use at the primary airport. Sectors are also combined during periods of low traffic and de-combined, or split, during high traffic periods.

3.1.3 Sector Teams / Control Positions

Aircraft within a sector are controlled by a team of one or more controllers. The distribution of tasks amongst members of the team can vary from facility to facility and between countries. In the United States there are two primary controller positions. The R-side or radar controller typically acts as the primary communicator and implementer of commands. Supporting the R-side controller is the D- side or data controller. The D-side controller updates automation

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[2] During observations at the Boston TRACON these divisions were identified as “positions.” “Positions” are equivalent to sectors and to preserve clarity and readability the term sectors is used exclusively in this thesis.

equipment and serves as the point of contact for coordination with other controllers. By regulation, both controllers are jointly responsible for sector operations; however, by, convention, typically the R-side controller is in a dominant role. At times of high traffic levels a third and forth controller can sometimes be added to serve as "Trackers" or "Hand-off" specialists. During low traffic periods, all of the functions may be combined and performed by a single controller.

3.2 Air Traffic Situation

In Figure 3–1, the air traffic situation represents the other controllers on the sector team and the key objects and events in and near the sector. The following sections describe important objects and sources of dynamics within the air traffic situation.

Aircraft

The aircraft controlled by controllers in both Centres and TRACONs operate under a variety of rules. Several types of aircraft can be present and there are important differences in the controllability and availability of intent information about each type:

IFR Aircraft. Aircraft flying under Instrument Flight Rules (IFR), are obliged to fly trajectories consistent with an air traffic controller's instructions. Controllers can issue commands to these aircraft that amend the trajectory. Consequently, future positions and the trajectory of IFR aircraft are generally stable and predictable.

VFR Aircraft. In contrast, aircraft flying under Visual Flight Rules (VFR) retain responsibility for separation from other aircraft and terrain clearance. Under most circumstances, VFR aircraft are free to maneuver independently. They are not obliged to inform the air traffic controller of any trajectory changes and in some cases will not be in communication with the controller. The future trajectory of aircraft in this category can be uncertain.

Flight Following Aircraft. VFR aircraft can request controllers to provide a flight following service where the controller provides advisories of potentially conflicting traffic. Aircraft receiving the flight following service retain responsibility for altering their trajectory to ensure separation from other aircraft, terrain and airspace.

Other Objects. Gliders, hot air balloons, rockets and other airborne man-made objects may also be present in the operational environment. In general, such objects are independent of controller commands and controllers have limited access to information about their intent and future trajectories.

Weather

The behaviour and trajectories of aircraft are impacted by the weather conditions in the physical environment. Components of the environment such as thunderstorms cells or areas of turbulence or icing influence the trajectories of aircraft directly through their impact on instantaneous aircraft motion and indirectly through their influence on pilot decision making and avoidance strategies. The movement of weather conditions are an additional source of dynamics as these features can appear to move dynamically in a manner similar to physical objects. For example, thunderstorm cells move in response to atmospheric forces.

Airspace

The controller's operational environment also contains key airspace elements. Navigational aids, such as radio beacons like Very High Frequency Omni-Directional Ranges (VORs), Nondirectional Radio Beacons (NDBs), and Very High Frequency Omni-Directional Ranges /Tactical Air Navigation (VORTACs), are examples of airspace elements. These elements are used for navigational purposes and are the basis for a series of airways and jet routes. Other airspace elements may include Instrument Landing Systems (ILSs), letters of agreement, standard flows, and standard operating procedures.

Regions of airspace where potentially hazardous activities occur can be designated as Special Use Airspace (SUA). Such regions of airspace can be designated as restricted or warning areas and can preclude aircraft from entering. SUAs are often associated with military airspace and/or activities.

Flight Data

A key part of the air traffic situation is the flight data, or aircraft flight plans describing proposed future routes of flight and aircraft characteristics. Each aircraft flying under IFR must file a flight plan describing the proposed route of flight, altitude, type of aircraft, and air speed. The flight plans establish both lateral and vertical expectations of aircraft behavior as well as important aircraft characteristics such as aircraft type and navigation capabilities. Flight plans provide common understandings of expected aircraft behaviors and future trajectories; this is particularly important in loss of communication situations where the flight plan provides the basis for assumptions on the actions that the pilot will take.

Descriptions of aircraft routes filed as part of a flight plan are a key element of flight data. The description of an aircraft's route of flight is composed of multiple types of airspace elements, from VORs to latitude/longitude coordinates, to jet routes or victor airways and arrival procedures.

ATC Clearances

Flight plan data forms the basis for an aircraft's ATC clearance. An ATC clearance is "an authorization by ATC, for the purpose of preventing collision between known aircraft, for an aircraft to proceed under specified conditions within controlled airspace" (Spence, 2001, Pg 137). A clearance contains at a minimum a clearance limit, description of the route of flight, and an altitude. Federal Aviation Administration (FAA) Order 7110.65 specifies the items that must be present in a valid clearance (FAA, 2004). A clearance can constrain an aircraft to fly fixed trajectories relative to the ground (e.g. "cleared present position direct Albany"), relative to the air (e.g. "fly heading 350") or can provide general constraints that provide flexibility to pilots (e.g. "deviations right approved, direct Belleair when able"). As described below, modifying each aircraft's clearance is the fundamental control mechanism available to a controller.

Other Personnel

The air traffic situation also models other personnel, primarily controllers, with whom controllers interact. The closest contact is with other members of the sector team, such as the collaboration between the R-side/D-side controller members of the sector team. Controllers coordinate control actions or pilot requests directly controllers of surrounding airspace. Controllers also interact with supervisors, particularly with respect to combining and de-combining sectors as well as the negotiation and implementation of traffic management initiatives.

3.3 The Air Traffic Control Task

Controllers perform a wide range of interdependent tasks. Extensive compilations of the tasks and goals of controllers have been produced by Rodgers and Drechsler (1993) and Endsley and Rodgers (1994). Based on observations developed in this research, seven categories of tasks were identified:

- separation tasks,
- monitoring tasks,
- constraint tasks,
- request tasks,

- coordination tasks,
- information tasks, and
- other tasks.

The tasks in each category are not performed independent of each other; for example coordination tasks may be driven in part by actions taken to perform separation tasks. The following sections describe each category of task.

Separation Tasks

The core service provided by air traffic controllers is ensuring that aircraft remain safely separated. Separation assurance is provided from other aircraft, terrain, weather, and airspace where potentially hazardous activities are occurring. The task requires the controller to project and evaluate the future positions of aircraft and status of airspace in order to detect and correct events like possible collisions. Typical separation standards in the enroute environment are 5 miles laterally and 1000 feet vertically. In terminal environments this can be reduced to 3 miles laterally and 1000 feet vertically.

In certain circumstances and regions of airspace, separation standards depend on the type of aircraft. Wake turbulence standards reflect the consequences of an encounter with the wake, or disturbed air, of another aircraft. These standards vary with the size of the aircraft involved. Separation standards also vary with the type of surveillance data available, distance aircraft are from surveillance sources, and the navigation systems being used by aircraft.

Monitoring Tasks

Controllers have a responsibility to monitor the conformance of aircraft to the current clearance and provide safety alerts to alert pilots to navigation or flight control errors. Controllers monitor current and projected states of the air traffic situation to ensure that aircraft are conforming to the existing ATC clearance within acceptable tolerances.

Constraint Tasks

Controllers have tasks related to the need to meet constraints on acceptable aircraft trajectories. There are several sources of these constraints including:

Traffic Management Initiatives. A common source of constraints are the need to meet traffic management spacing requirements on aircraft with common destinations or routes. Key forms of flow restrictions include miles-in-trail restrictions, minutes-in-trail restrictions, and routing restrictions. Adjacent controllers may dynamically place constraints on the arrangement of aircraft crossing facility boundaries; for example they may require aircraft to cross the sector boundary in a single stream or with no aircraft stacked on top of each other at different altitudes.

Procedure and Letter Of Agreement (LOA) Requirements. Repeatedly occurring constraints are often codified into standard procedures that regulate how aircraft cross the boundary from one sector to the next. Interface procedures have roots in both specific Standard Operating Procedures (SOPs) as well as Letters of Agreement (LOAs) that govern the interactions between facilities. For example, interface procedures may place requirements on aircraft trajectories laterally, requiring aircraft to be cleared to follow a particular path, vertically, requiring aircraft to be at a particular altitude, longitudinally, requiring a particular speed to be assigned, or combinations thereof.

Request Tasks

Tasks requiring the modification of aircraft trajectories are also the product of requests from pilots. These request tasks are often due to weather deviations. The presence of adverse or different from forecast weather conditions are a key source of requests for modifications to an aircrafts trajectory. The presence of convective weather (e.g. thunderstorms) often requires aircraft to deviate from the assigned course. Wind or turbulence can create uneconomic and/or uncomfortable ride conditions and can prompt pilots to request new altitudes or routings. In response to changes in the aircraft's weight as fuel is burned, pilots will request amendments to an aircraft's cruising altitude.

Coordination Tasks

A fifth category of tasks includes communicating and coordinating with other controllers, and pilots. These tasks can take several forms including:

Implementing Requests from Other Controllers. Controllers receive requests from controllers of surrounding airspace to modify an aircraft altitude or trajectory in order to solve a problem that will occur in the requesting controller's airspace.

Handoffs. Two forms of handoff tasks occur: radar handoffs in which "ownership" of an aircraft is passed from one sector to another, and communication transfers where pilots are instructed to contact the next sector on a different communications frequency.

Pointouts. In a pointout, a controller coordinates the use of airspace along a common boundary with an adjacent controller. Often a point-out occurs when one sector "borrows" a portion of an adjacent sector's airspace with respect to a particular aircraft for a short period of time. Point-outs also occur when an aircraft is simply passing less than the half the applicable minimum separation distance from the airspace boundary (FAA, 2004). Point-outs occur both laterally and vertically. Where aircraft are continually clipping parts of an adjacent sector, airspace changes, or automated handoff procedures (AITs) may be used to reduce the frequency with which point-outs are required.

Information Tasks

A sixth category of tasks encompasses various forms of information management. Decision support tools, including conflict predictors, trajectory prediction, automated conformance monitoring and distribution of flight data all depend on the maintenance of accurate representations of current clearances in ground-based automation. Automation systems rely on aircraft route descriptions for look ahead conflict prediction, and distribution of flight data to facilities and control positions. As controllers modify clearances, a key task is ensuring that the representation of the clearance in automation tools such as the User Request Evaluation Tool (URET) and the Host computer system is kept up-to-date.

*C*ontrollers also act as important information sources for pilots. Controllers disseminate altimeter settings, weather conditions, ride reports, and other operational information used by pilots. In cases where automation links are not available, such as during maintenance failures, or interfaces with small airports and/or international facilities, controllers also become responsible for the distribution of flight data and the passing of estimated times when aircraft will cross sector/facility boundaries.

Other Tasks

Depending on the airspace controllers may also have tasks that including providing advisory services such as flight following, providing approach clearances and services, providing full route clearances to departures from non-towered or air filed aircraft. Dealing with "pop-up" aircraft, or aircraft transitioning from VFR to IFR, and emergencies are additional tasks. Controllers are also responsible for ensuring that other controllers are not overwhelmed. In cases where too many aircraft are present in a downstream sector, or disruptions occur at a destination airport, controllers may also have to hold aircraft within their airspace. The ATC system also provides alerting services and supports search and rescue activities.

The discussion above shows that the controller's task encompasses far more than the avoidance of conflicts. Many of these tasks place requirements and/or restrictions on the relationships between aircraft, or between aircraft and other objects. For example, separation tasks impose minimum distances between two aircraft. In order to capture this richness, the term “interactions” will be used to encompass the range of factors such as separation standards, traffic management initiatives, or procedures that place conditions on the relationship between two or more objects (e.g. aircraft, or aircraft and airspace, aircraft and weather). Two aircraft interact if the task places a requirement or restriction on the relationship between the aircraft.

3.4 Performing the Task

In order to perform these tasks, controllers transform data about the current state of the situation into commands that modify an aircraft’s clearance and hence future states of the air traffic situation. The following sections describe the sources of data available to the controller and the mechanisms by which an aircraft’s trajectory can be altered.

3.4.1 Data Sources

The primary inputs to a controller are the outputs of decision support tools and communication systems. The following sections discuss these sources.

Communication Systems

Communication systems are one of the most important sources of information about the current state of the environment. Through primarily radios and telephone systems, controllers are able to obtain information about the current air traffic situation from pilots, and other controllers. For example, in areas where there is a lack of radar coverage, pilots will report their current position. Pilots may also report reaching or leaving an altitude. The latter is useful in certain situations even in radar coverage as separation standards allow controllers to assign an altitude once an aircraft has reported leaving that altitude (FAA, 2004).

Radio communication requires pilots and controllers to share a common channel; this can create problems with overlapping communications that typically drown both parties out with a painful “squeal.” Communication between pilots and controllers uses standardized phraseology in order to reduce ambiguity, increase clarity and suppress possible sources of error (McMillan, 1998).

Controllers use the Voice Switching and Control System (VSCS) interface to control the configuration of Very High Frequency (VHF) band radio frequencies used for two-way communications between the controller and multiple pilots. In large sectors, controllers may transmit and receive on multiple frequencies. The VSCS also controls the use of interline telephone circuits connecting a controller with those operating adjacent sectors. Alternately referred to as “interlines”, “handoff lines” “interphones” or “land lines”, these dedicated circuits allow controllers to communicate with controllers across the aisle, within the same building, or operating neighboring airspace from a different state. The circuits can connect with surrounding airspace controllers, controllers working in control towers at nearby airports, or flight service stations.

Surveillance Systems

Surveillance systems provide estimates of current weather and aircraft positions. Two types of radar provide access to the current positions of aircraft. Secondary radar uses timing pulses and replies from an aircraft’s transponder to determine an aircraft’s lateral position and altitude. All aircraft equipped with an operating transponder can be observed, including both IFR and VFR aircraft if appropriately equipped. The use of discrete transponder codes allows automation systems to associate surveillance information such as radar targets with other information such as aircraft flight plans.

Aircraft states are also surveilled through the use of primary radar. Primary radar times the delay between transmission and reception of a pulse reflected off of an aircraft to estimate the distance and azimuth of the aircraft from the radar site. Altitude information is generally not available from a primary radar source but primary radar can observe aircraft flying without a transponder. Typically controllers do not use primary radar sources as many distracting objects (e.g. flocks of birds, trains) can also be interpreted as radar returns by the data processing software.

In both enroute and terminal environments, radar updates are limited by the speed of rotation of the radar system. In terminal environments, typical radars have update times of 4.8 seconds (Davison-Reynolds, 2006); in enroute environments, longer range radars rotate more slowly and the time between updates is typically on the order of 12 seconds. Nolan (2004) provides additional details of radar surveillance systems and data processing.

Convective weather in the physical environment is surveilled through primary radar and specialized weather radars. For enroute controllers, the National Weather Services (NEXRAD) product uses multiple scans of a specialized weather radar to build a three dimensional image of the water content of the atmosphere. The Weather and Radar Processor (WARP) transforms NEXRAD data for display on a controller’s primary situation display, discussed below (Brown, 2004a). The process has an update period of six minutes. Due to the speed with which weather conditions can change, this can create significant inconsistencies between the NEXRAD product and the information available to pilots from onboard weather radar with faster update rates.

Aircraft Positions & the Situation Display

A controller's situation display is the primary decision support tool. The situation display provides an estimate of the current state of the air traffic situation, providing one of the bases for estimating future states. The situation display depicts the current and historical positions and altitude of aircraft as well as convective weather, airspace boundaries, locations of navigational references, and aircraft data blocks.

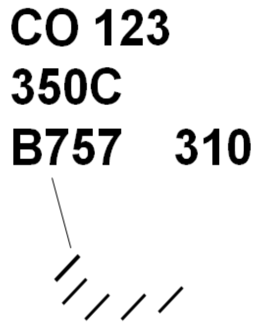

Figure 3–4. Example data block.

An example of a data block is shown in Figure 3–4. An aircraft's current position and historical radar returns are shown as slashes, allowing future trajectories and current states such as aircraft track angle to be inferred. The data block displays information associated or tagged with each radar return; this includes information such as the aircraft's call sign, altitude, estimated groundspeed, the sector with control responsibility for the aircraft, handoff status, and other coordinated information (Mills *et al.*, 2002).

Lists of aircraft expected to arrive in the sector are typically displayed on the primary display. In addition, lists of aircraft no longer associated with radar returns (coast mode), aircraft in conflict, aircraft operating below minimum safe altitudes, and other safety alerts are displayed. A keyboard and trackball allow a controller to interact with information displayed and perform electronic coordination such as offering an aircraft for handoff to an adjacent sector.

Flight Data

In addition to radar displays showing current aircraft positions, controllers have access to each aircraft's flight data which describes expected future positions of the aircraft. Traditionally flight data has been presented in the form of flight progress strips. The flight strips are physical artefacts that can be written on, moved, and re-arranged. Flight strips are arranged on a strip board and are typically organized by some combination of common navigation point, altitude and time. Strips contain an estimate of the time the aircraft will reach a common navigational fix in the sector.

The projected times at fixes has been previously reported as a key characteristic of strips that allows a controller to use the information on the strip to project future states of the air traffic situation (Fields *et al.*, 1998). Strips are typically printed and distributed to a sector twenty minutes before the aircraft is expected to enter the sector (Moertl *et al.*, 2002). Maintaining the strips serves as a key redundancy technique, retaining at least minimal information about the current aircraft in an air traffic situation and their expected route of flight in the event of a loss of primary surveillance sources.

URET

During the course of the research reported in this thesis, the FAA deployed a new decision support tool to en route controllers that replaced paper flight strips as the means of accessing flight data.[3] URET is a medium term conflict alert, trajectory evaluator that replaces flight strips and provides a new interface to stored flight plan data. Keyboard and trackball input devices are used to amend flight plan data, trial plan clearance amendments such as a re-route, and access other URET functionality.

Several key changes to controller work processes have been reported as a consequence of the introduction of URET. The removal of flight strips has significantly reduced the amount of time required for strip maintenance, for example updating strip positions, pruning strips of aircraft that have left the sector, and adding strips of new aircraft. The URET interface makes it significantly easier for controllers to enter clearance amendments and captures amendments that were previously only recorded on the paper flight strips.

Other Decision Support Tools and Information Sources

Control positions also contain decision support tools that provide guidance for sequencing and spacing of aircraft. The Traffic Management Advisor (TMA) provides guidance for the sequencing of arrivals to high traffic airports by displaying the number of minutes that must be gained or lost directly in the data block. Other aids such as the Converging Runway Display Aid (CRDA) create ghost images of the relative placement of aircraft in order to help synchronize and sequence arrivals to the same airport being controlled by separate sectors.

In some enroute facilities a projection of high volume traffic flows is presented in a central location amongst the sector workstations in an area, providing controllers a quick glance

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[3] Flight strips are still used in sectors performing non-radar operations and Canadian en route facilities.

overview of traffic conditions beyond their immediate sector boundaries. Electronic displays summarizing current runway in use, winds and altimeter settings are also present.

Many of the descriptions of an aircraft's route of flight use references that are well beyond the sector boundaries; in determining which way an aircraft will turn to reach an unfamiliar airport, the controller may need to interpret obscure references such as "IO5" (Brown, 2004b). Several sources of data for interpreting such references are provided to controllers. Large maps of each sectors airspace are presented as part of back illuminated displays above each sector workstation. Sector binders, containing approach charts, airport surface maps, and other pertinent information are also available at each sector workstation. A new decision support tool, the En Route Information Display System (ERIDS), has been deployed to provide electronic access to some of these data sources including local standard operating procedures, Letters of Agreement (LOAs), and the content of sector binders (Sollenberger *et al.*, 2004).

3.4.2 Command Mechanisms

Based on the information obtained from these sources, controllers identify and implement changes to aircraft clearances that ensure future aircraft trajectories satisfy the current task. The primary command mechanism is communication systems that allow the controller to implement changes to aircraft clearances and modify the dynamics of the air traffic situation. Clearance amendments alter an aircraft's route of flight, altitude, speed, and/or rate of climb /descent

By amending the clearance, a controller can constrain aircraft behavior (e.g. "do not exceed 260 knots") or place requirements on aircraft behavior (e.g. "cross a location at an assigned altitude"). A clearance may not uniquely determine an aircraft's trajectory. For example, controllers may command a pilot to descend and maintain an altitude at the pilot's discretion.

Commands are implemented through verbal instructions using the same communication systems providing information about current states of the operational environment (Section 3.4.1). The implementation of commands is a serial process, and requires pilots to read back the instruction in order to confirm it was correctly understood. Due to the latencies in surveillance update rates (Section 3.4.1), it can take upwards of a minute before an enroute controller can verify that the pilot is correctly complying with a simple instruction.

3.5 Chapter Summary

Air traffic controllers have responsibility for distinct blocks of airspace, or sectors. Within the sector, controllers perform multiple tasks ranging from separating aircraft to updating and maintaining flight data. In order to perform these tasks, multiple data sources provide controllers access to information about current states of the operational environment (e.g. the situation display) as well as intent information useful for projecting future states (e.g. flight data). Based on the information provided by these sources, controllers modify aircraft clearances in order to satisfy the requirements of the ATC task.

CHAPTER 4 Approach, Methods and Example Observations of Cognitive Complexity and Structure

This chapter presents the approach and methods used to investigate the ATC system described in Chapter 3.

4.1 Approach

In order to examine the impact of structure on the cognitive complexity of performing ATC tasks, a deep examination of the ATC system was conducted from a variety of perspectives. The approach was multi-faceted and drew heavily from cognitive ethnography methods, part of the broader family of cognitive task analysis. Cognitive ethnography methods were attractive as they provide powerful means of developing insight into the relationships between humans and their task environments (Hollan *et al.*, 2000; Ball and Ormerod, 2000) and have been successfully used to study pilots performing tasks within airline cockpits (Hutchins, 1995). As described by Hollan *et al.* (2000), "cognitive ethnography is not any single data collection or analysis technique. Rather it brings together many specific [and complementary] techniques, some of which may have been developed and refined in other disciplines (e.g., interviewing, surveys, participant observation, and video and audio recording)."

The approach used in this thesis took advantage of many of these techniques, as well as complementary quantitative analyses, to investigate multiple aspects of the relationship between cognitive complexity and structure. These aspects included identifying key complexity factors, identifying core elements of structure, and developing hypotheses of the mechanisms by which structure influences controller cognitive complexity. Specific parts of the hypothesized mechanisms were probed through the use of part-task experiments.

Methods and example results are presented in this chapter; details of the part-task experiments are provided in Chapter 7. As multiple, overlapping data collection and analysis methods were used in most of these investigations, each of the core methods is described separately below to avoid repetition. Examples of the types of data obtained by each specific method are presented with each method description. Chapters 5 and 6 use the key results from these investigations to develop hypotheses of how structure impacts controller working mental models and can act as a complexity reducing mechanism.

Figure 4–1 shows the model of the operational environment described in Chapter 3. As illustrated in the figure, a combination of observational and analytic methods were used to investigate sources of structure in the air traffic situation, the controller's task, and the cognitive processes used by controllers to perform the task. The methods included:

- "*in situ*" observations and interviews,
- analysis of the air traffic situation, and
- analysis of controller-pilot communications.

These methods created a diverse range of observations useful for probing internal constructs that are not directly observable, such as cognitive complexity (Mogford, 1994b).

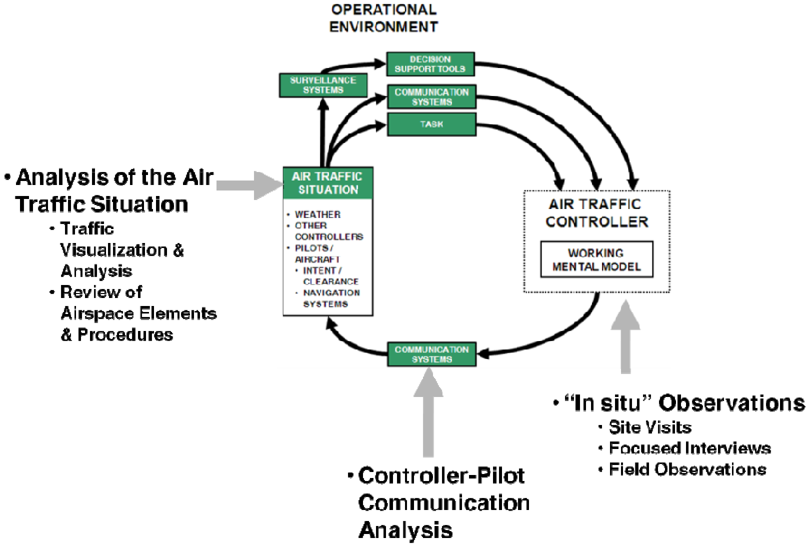

Figure 4–1. **Methods used in the cognitive ethnographic approach.**

4.2 "In Situ" Observations

In order to develop insight into the ATC task, ethnographic techniques were used to collect *in situ* observations of controllers controlling traffic in a range of enroute and terminal facilities. As described in the following sections, focused interviews and field observations were used during site visits to gain insight into:

- key factors affecting cognitive complexity,
- sources of structure in the air traffic situation,
- influences of structure on the operational environment, and

- how structure impacts how controllers perform their task.

Table 4–2. Subjects of focused interviews.

4.2.1 Method

Site Visits

A series of site visits were made to multiple en route and terminal ATC facilities. Table 4–1 lists the number of sectors and types of operations observed at each facility. During the site visits, focused interviews were conducted with key personnel. Field observations were collected of controllers and traffic flow managers performing their duties. The personnel available for interviews and amount of observation time was subject to operational requirements and varied between sectors and facilities.

Table 4–1. Site visit facilities.

FACILITY NAME	FACILITY TYPE	TYPE OF OPERATIONS OBSERVED	# OF SECTORS OBSERVED
Boston TRACON	**TRACON**	**Terminal**	**4**
Boston Center	**CENTER**	**En route, Training**	**6**
Cleveland Center	**CENTER**	**En route, Traffic Management Unit**	**6**
Washington Center	**CENTER**	**En route**	**2**
Edmonton Center	**CENTER**	**Enroute, Terminal**	**5**
Montreal Center	**CENTER**	**En route**	**1**
Vancouver Center	**CENTER**	**En route**	**2**

Extensive multi-day observations were collected at Boston Center, Cleveland Center and the Boston TRACON. Other facilities were visited for a single day. In most cases, each sector was observed for more than two hours and with several different controllers. A wide range of operating conditions were observed including multiple runway configurations (e.g. Boston TRACON), various times-of-day and times-of-year, limited communication and surveillance environments (e.g. Edmonton Centre), and sectors of various sizes. At each site visit focused interviews were conducted and field observations collected.

Focused Interviews

During the site visits, focused interviews were conducted with active and retired controllers, supervisors, traffic management personnel, and training personnel. Open-ended questions were posed during the focused interviews and active engagement with the interview subject used to clarify responses, elicit illustrative examples, and understand complexity issues specific to the controller's airspace. Focused interviews have the benefit of allowing interviewers to clarify subject responses, adapt additional questions to reinforce initial comments, and pursue new topics identified in the course of the interview (Gromelski *et al.*, 1992).

FACILITY TYPE	PERSONNEL INTERVIEWED	NUMBER
Terminal	**Controllers**	**9**
	Traffic Management Personnel	**1**
	Training Specialists	**1**
Enroute	**Controllers**	**15**
	Traffic Management Personnel	**5**
	Training Specialists	**2**
Total		**33**

A summary of the questions posed during the interviews appears in Table 10–1, Table 10–2, Table 10–3 in Appendix I. The questions spanned a range of areas designed to probe the sources of complexity and the role of structure. Controllers were asked to identify key complexity factors; questions such as "what characteristics make a sector more / less difficult?" were used to investigate how key structural features affect controller perceived complexity.

Questions for traffic flow management personnel focused on understanding their perceptions of controller cognitive complexity and identifying the factors they used to determine when to impose traffic management restrictions. Participants (controllers, supervisors, traffic management personnel) were also asked to rank the sectors in their area of specialization from most complex to least; follow-up questions probed the reasons behind their sector rankings. Questions for training personnel probed how controllers learn the structure in an airspace as well as how trainees are taught to manage cognitive complexity.

The interviews took place both in the context of observing controllers and traffic management personnel performing their duties as well as during break sessions. Participant responses were recorded as field notes for subsequent synthesis and analysis. As shown in Table 4–2, more than 30 ATC personnel were interviewed. Several participants were interviewed more than once during return visits and were able to clarify and expand on previous responses.

Field Observations of the ATC Task

Figure 4–2. Perspective of over the shoulder observations (from FAA, 2006).

Passive observation and contextual inquiry methods were used to collect field observations of ATC operations. During high traffic periods, passive observations were made of controller actions, commands, personnel interacted with, and the resulting trajectories of aircraft. Traffic and workload permitting, contextual inquiry techniques were used. For example, controllers were asked to describe the current situation and identify potential sources of complexity. Contextual inquiry techniques use engagement with the participants under observation in order to maximize the researcher's understanding of a domain (Beyer and Holtzblatt, 1998). The active engagement with the controllers provided important opportunities to investigate specific cognitive complexity issues such as the impact of coordination and the consequences of having a mix of aircraft present in the airspace.

Field observations were collected by monitoring the controllers' work space, typically from a seated position next to the controller (similar to the perspective shown in Figure 4–2). Intra-controller and controller-pilot communications were monitored using an extra headset. During the observation periods, controllers would often explain a set of control actions and the basis for performing them. Particular attention was paid to identifying controller tasks, actions, the key personnel interacted with, and the sources used to gain information about the current state of the system and pilot intent.

Observations were collected in the form of field notes describing controller actions. Controller comments, including sector specific complexity factors, were also recorded. As the ATC task is highly spatial in nature, the field notes were supplemented with map based spatial depictions of the locations of aircraft during key events. For example, in order to document the relationship of handoff locations to the underlying airspace structure, the locations of both radar and communication handoffs were recorded on maps of the sector under observation (see Appendix II for an example).

Initial observations focused on identifying key features of the sectors' operational environment that appeared to contribute towards cognitive complexity. For example, typical sector operations, and standard procedures within the sector were identified and cross-checked with controllers. As the observer gained familiarity with sector operations, the focus shifted to identifying unique or particularly complex events. Controllers were encouraged to identify complexity factors specific to the airspace being worked as well as their strategies for regulating and mitigating cognitive complexity.

4.2.2 Example Observations

The field observations and focused interviews conducted during the site visits identified key complexity factors and several examples of airspace structure playing key roles in the controller's task. This section provides brief examples of the observations obtained using the methods described above.

Key Complexity Factors

Responses to focused interview questions were collated and a list of key complexity factors was compiled (Table 4–3). No attempt was made to rank or weigh the factors. The factors were found to fall into three categories: *Airspace Factors*, *Traffic Factors*, and *Operational Constraints*.

Airspace Factors are those factors related to characteristics of the airspace that is being controlled. These factors include properties such as the distribution of navigational aids as well as a sector's shape and its implications for coordination activities. In general, *Airspace Factors* are quasi-static and are characteristics of the underlying context within which a traffic load exists.

Traffic Factors, are transient factors that depend on the instantaneous distribution of traffic in the sector. Many *Traffic Factors* are related to or are consequences of *Airspace Factors*. For example the location of closest approach of an aircraft encounter will depend on the routes flown by each aircraft; these routes are often a function of the standard flows through the airspace. The contribution to cognitive complexity of the encounter can be strongly influenced by the relation of the point of closest approach to other *Airspace Factors* such as the sector boundary.

Operational Constraints are additional operational requirements that place restrictions on possible control actions. These factors tend to represent short-term or temporary variations in operational conditions.

Sector complexity rankings were consistent with the key factors shown in Table 4–3. Responses indicated that a lack of well-defined flows of aircraft through a sector played a key role in participants ranking a sector as more difficult. For example, for two of the three most complex sectors ranked within one area of specialization at Cleveland Center, the primary source of complexity was given as the lack of well-defined flows.

Table 4–3. Key factors reported by controllers as influencing complexity.

AIRSPACE FACTORS
• Sector dimensions *(Shape, physical size, Number of Flight Levels, Relevant airspace beyond sector boundaries)*
• Letters of Agreement / Standardized Procedures
• Number and position of standard ingress / egress points
• Spatial distribution of airways / Navigational aids *(Usefulness of placement)*
• Standard flows *(Number of, Orientation relative to sector shape, Trajectory complexity, Lack of)*
• Interactions between standard flows *(crossing points, merge points)*
• Coordination with other controllers *(Hand-offs, Point-outs)*
TRAFFIC FACTORS
• Density of traffic *(Clustering, Sector-wide)*
• Aircraft encounters *(Number of, Distance between aircraft, Relative speed between aircraft, Location of point of closest approach (near airspace boundary, merge points etc…), Difficulty in identifying, Sensitivity to controller's actions)*
• Ranges of aircraft performance *(Aircraft types (Boeing 747 vs Cessna 172), Pilot abilities, Control services required (IFR vs VFR))* • Number of aircraft in transition *(Altitude / Heading / Speed)* • Sector transit time • Relationship of aircraft to standard flows *(Presence of non-standard aircraft)*
OPERATIONAL CONSTRAINTS
• Restrictions on available airspace *(Presence of convective weather, Activation of Special Use Airspace, Aircraft in holding patterns)*
• Buffering capacity
• Procedural restrictions *(Noise abatement procedures, Traffic management initiatives (e.g. miles-in-trail requirements))*
• Communication limitations
• Wind Effects *(Direction, strength, changes)*

Role of Structure

The field observations showed structure has an important role in how a controller understands an air traffic situation. Examples of observations consistent with this included:

Aircraft Described by Relationship To Structural Features in a Sector. During the field observations, controllers regularly described the air traffic situation, and aircraft within it, by their relationship to structural features in the sector. For example, controllers repeatedly used references to features of the underlying traffic patterns such a common altitude, membership in a flow or stream, or position with respect to common physical location. Controllers were observed using techniques to reinforce membership in flows; several cases were observed of controllers using a common offset of the data blocks for aircraft within a flow.

Complexity Increased by Non Standard Aircraft. Aircraft flying trajectories inconsistent with the structural features were highlighted as "non standard" and described as increasing the complexity of the situation. For example, aircraft operating outside the standard routes in an airspace appeared to require additional attention and were described as being a key source of complexity. As described by a Boston TRACON controller: "Non-standard aircraft are out of flow" and this "leads to surprises."[4] "Moving somebody off the standard flow is bad" as it adds "too many things to worry about."[5] Aircraft deviating from standard procedures were reported as creating a "snowball effect" often requiring increased coordination to resolve issues typically avoided by use of the original procedure (Davison and Hansman, 2003). These observations are consistent with initial findings reported by Li *et al.* (2008) of a part-task ATC experiment; participants rated 86% of the aircraft that were "off route" as having a higher effective complexity than a baseline aircraft.

Airspace Boundaries and Controller Planning

The focused interviews and field observations also showed that structure in the form of airspace boundaries is a key factor in controller planning. Airspace boundaries appear to play key roles in determining when controllers perform the planning task.

Early Planning. In the field observations, controllers described performing planning tasks early, prior to aircraft entering the sector. Controllers described the importance of identifying "issues" or "problems" as early as possible. In the words of one controller, controllers "never think about right now – looking, 2, 3, 5 minutes ahead."[6] Controllers are "always prepared for [their] next action" and that as a controller, one always "want[s] to know [your] next move."[7]

Planning and projecting occurred before aircraft entered the sector. Controllers are "doing evaluations even before [they] get [the] handoff"[8] and creating plans "before [an] aircraft ever arrives… to approve a reroute, look ahead and stop a guy at an altitude." Another controller stated that it was "important to get things done early" and "[you] don't want to work near [the]

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[4] October 2001, Cleveland Center, Air Traffic Controller.

[5] January 25, 2002, Boston TRACON, Air Traffic Controller.

[6] October 19, 2001, Cleveland Center, Air Traffic Controller.

[7] October 2001, Cleveland Center, Air Traffic Controller.

[8] October 19, 2001, Cleveland Center, Air Traffic Controller.

exit edge [of the sector]."[9] This was consistent with qualitative observations of the timing of controller commands during field observations. Controllers stated that when aircraft are close to the sector's exit boundary, higher amplitude commands must be given in order to meet the exit constraints. For example, sharper turns and more aggressive speed reductions may be necessary to meet an in-trail spacing restriction.

Early Handoff of Aircraft. In the field observations, controllers appeared to transfer aircraft to the next sector as quickly as possible. This often occurred a significant distance from the sector boundary. Controllers described "shipping" aircraft as the "name of [the] game: get rid of my airplanes."[10] Typical of the responses to probes as to how this reduced cognitive complexity was "once been shipped, [the aircraft is] no longer relevant."[11] This is consistent with the observations described above of early evaluation and planning of aircraft

Graphical field notes showed evidence of both the early planning and early handoff effects. Figure 4–3 reproduces field observations tracking the approximate location of handoff activities observed during one observation session in one sector within the Boston TRACON. The figure shows the approximate location of initial radio contacts, close to the Providence arrival fix and upstream of the formal airspace boundary. A parallel effect was observed at the downstream sector boundary. The shaded region approximates the area controllers appeared to be focusing significant attention on while controlling this sector.

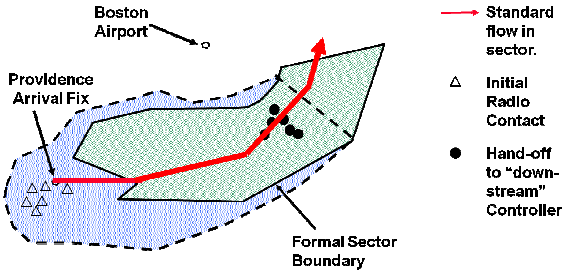

Figure 4–3. Example of observations of handoff locations and approximate boundary of controller attention for a sector within Boston TRACON.

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[9] October 19, 2001, Cleveland Center, Air Traffic Controller.

[10] December 2000, Boston TRACON, Training Unit personnel.

[11] October 19, 2001, Cleveland Center, Traffic Management Unit personnel.

4.3 Analysis of the Air Traffic Situation

As part of the cognitive ethnographic approach, both internal and external resources and their impact on decision-making were examined (Hollan *et al.,* 2000). In addition to direct observations of controllers, two key methods were used to analyze the air traffic situation:

- visualization and analysis of aircraft trajectories, and
- a review of airspace elements and procedures.

Both methods focused on identifying examples of structure and their influence on the controller's task and were used to corroborate and complement the observations and findings described above. The following sections describe each method.

4.3.1 Traffic Visualization and Analysis

Method

In order to develop a deeper understanding of the controller's task and corroborate initial findings developed from the "in situ" observations, visualizations of aircraft trajectories were developed from historical radar track data. As shown in Table 4–4, data for aircraft trajectories through the United States and Canada were obtained for several 24 hour periods between 1998 and 2005; the source of traffic data was the Enhanced Traffic Management System (ETMS).

Table 4–4. ETMS data.

ETMS DATA DATES
January 22, 1998
April 20, 2000
October 16-19, 2001
October 16, 2003
October 13, 2004
July 28, 2005

ETMS collects messages sent by the automation systems at each ATC facility detailing aircraft flight plans, positions, and trajectory events.[12] ETMS data records aircraft positions at approximately one-minute intervals and includes aircraft latitude / longitude positions, altitude, estimated ground speeds and a time stamp, as well as other aircraft states such as origin, destination and aircraft type. Traffic data consists of sets of ordered three dimensional (latitude, longitude, altitude) time stamped points. Due to the high volatility in reported ground speeds, constant velocity extrapolation was used to connect consecutive time-stamped points. An

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[12] The ETMS data had been filtered to remove military and other potentially sensitive aircraft, and thus may under-represent the real traffic situation.

example of the trajectory of an aircraft is shown in Figure 4–4. The "x"s mark the locations of individual radar "hits."

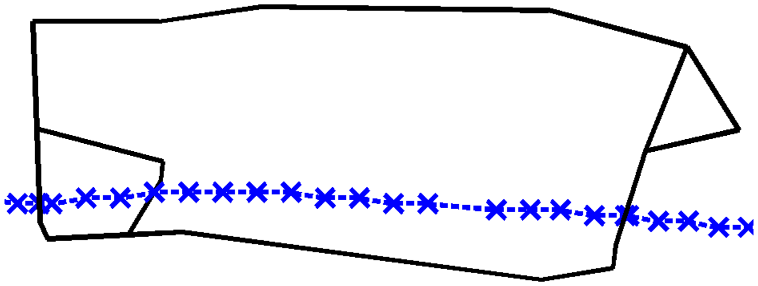

Figure 4–4. Track of single aircraft through Utica sector in Boston Center.

Figure 4–4 was created with the Enhanced MATLAB Graphics Engine (EMAGE) tool, a MATLAB interface developed to support the parsing and integration of multiple sources of radar traffic data using a common set of analysis tools and visualizations.[13] Filtering algorithms allowed the traffic data to be filtered by aircraft origin and destination, aircraft type, manufacturer, weight class and airline, sector entry/exit properties such as altitude, heading, and type of entry (lateral / vertical) and average climb / descent rates through the sector. Data could also be filtered for the portions of a trajectory prior to, within, or after a sector. These filtering techniques supported detailed examination of structural elements such as individual flows.

ETMS track data often contains spurious and incorrectly correlated data points, particularly in the vertical dimension. Algorithms were developed to remove excessive and unrealizable jumps in aircraft trajectories. For example, consecutive radar hits requiring aircraft speeds of 18,000+ mph or climb/descent rates in excess of 4,000 feet / minute were excluded from the data set.

Development of the EMAGE tool enabled a variety of perspectives of system operation to be developed and used for analysis. These perspectives included:

- radar tracks,
- track density,
- instantaneous traffic situations, and
- fast-time movies of traffic behavior.

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[13] This process reduces approximately 1.5 GB of position report data for a single day's worth of traffic to a more manageable 5-10 MB for a typical sector.

Radar Tracks. In order to understand the typical patterns of aircraft behavior in individual sectors, visualizations of all trajectories through and near a sector were created. The visualizations allowed three dimensional rotations to be shown, allowing the relationships between different flows within a sector to be analyzed.

Traffic Density. The EMAGE tool also provides capabilities for visualizing aircraft density. Thresholding techniques suppress infrequent aircraft tracks in the density images by making parts of an image with densities less than a minimum threshold transparent. In order to maximize the resolution of color scales used to depict density values, densities above maximum thresholds were capped at the maximum threshold value.

Instantaneous Traffic Situations. In addition to the analyses of aggregate aircraft behavior, representations of instantaneous traffic situations as would be viewed by a controller were created. Combining visualizations of an instantaneous traffic situation and the underlying density patterns supported corrobration of controller descriptions of sector operations.

Fast-time Movies of Aircraft Situations. Multiple time sequenced representations of instantaneous traffic situations were combined into fast-time movies. These movies provided opportunities to observe a larger variation in the types of situations and configurations of aircraft than possible using solely "in situ" observations.

The visualizations developed using these perspectives supported corroboration of observations developed during the site visits including supportive evidence of important structural features such as aircraft flows. They also helped overcome practical constraints that limited the number of site visits that could be conducted. This expanded the number of sectors observed and timescale over which sectors observations could be collected. Traffic visualizations were also generated using ETMS data obtained through Flight Explorer software (www.flightexplorer.com). This allowed further observations of system level effects during convective weather events.

Example Results

Regular, Sector Specific, Patterns in Aircraft Trajectories Visualizations of traffic density supported analysis of the presence of regular, repeated patterns in aircraft trajectories. Consistent with field observations and focused interview results, most of the more than 30 individual sectors examined had evidence of standard flows and points with high concentrations of traffic. Figure 4–5 shows an example of the density of aircraft for 24 hours of traffic through the Utica sector in Boston Center. Higher density (red/darker regions of the plot) show the concentration of aircraft into a primary east-to-west standard flow, consistent with the descriptions of sector operations collected during the site visit to the facility.

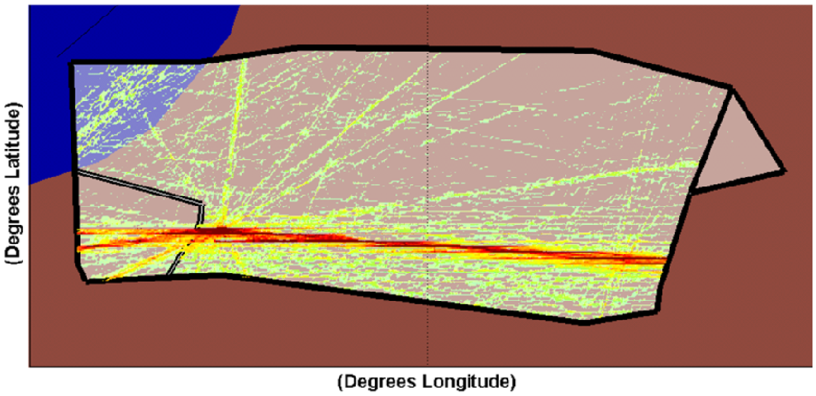

Figure 4–5. Density plot showing standard flow through Utica sector in Boston Center

Structure in Vertical Dimension ETMS data was used to analyze vertical behavior of aircraft. Visualizations showed clear evidence of structure in the form of discrete altitude levels. The discrete altitude levels are easily identified in Figure 4–6 which shows a profile view of traffic in the same sector as Figure 4–5.

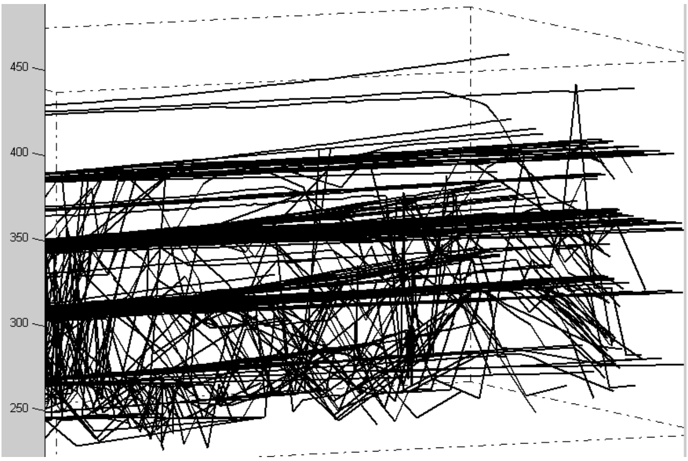

Figure 4–6. Profile view of traffic shows vertical structure in form of discrete altitude levels.

Early Handoffs. Visualizations and analysis of traffic data were used with secondary sources of controller activity to corroborate and develop quantitative support of field observations such as the handoff of aircraft prior to reaching a sector's boundary (see Section 4.2.2). TH or track messages archived within the Host computer system include fields specifying the controlling and receiving sector. Traffic data and corresponding Host computer messages for two flights through Memphis Center were obtained. The relative location of handoffs to key elements of structure such as aircraft flows and sector boundaries was examined by correlating track data with handoff message timing.

Figure 4–7 shows an example of electronic handoff locations in relation to the trajectory for one aircraft passing through several Memphis Center sectors. The white arrows show the location of the handoff and the boundary to which it corresponds. The locations of the handoffs are consistent with the use of early electronic handoffs. The early acceptance of the handoff by the receiving controller is consistent with the early planning and transfer of control concepts discussed in Section 4.2.2 above. The far right sector of the figure also highlights the importance of recognizing the three-dimensional nature of airspace structure. Sector 32 overlies sector 31 and hence the handoff from 31 to 32 is a vertical transition.

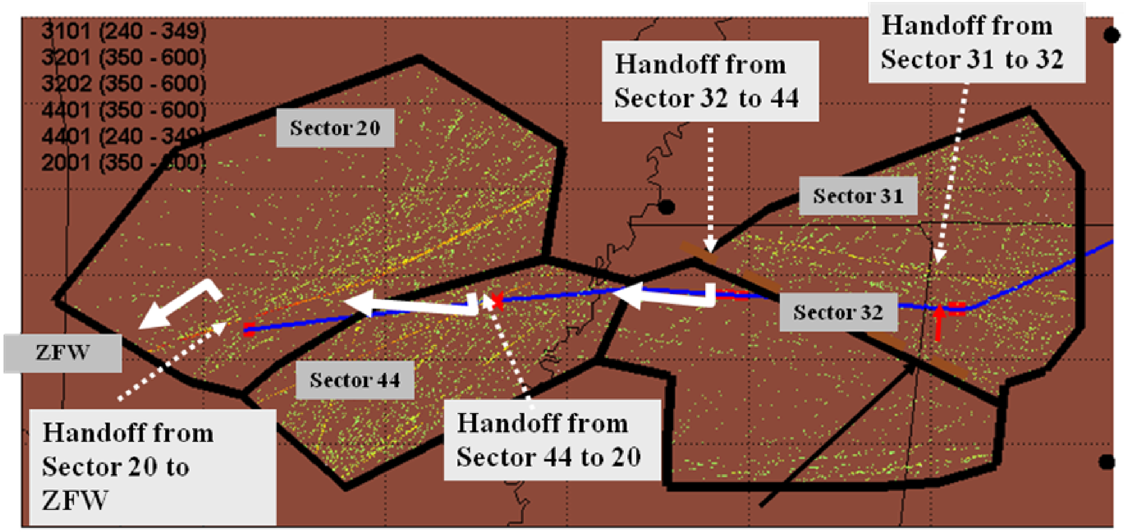

Figure 4–7. **Aircraft trajectory (blue) and handoff locations (white arrows) for aircraft trajectory through Memphis Center.**

4.3.2 *Reviews of Airspace Elements and Procedures*

In order to identify examples of the sources of structure identified in the focused interviews, field observations and traffic analysis, a comprehensive review was performed of the formal documentation of airspace and procedures. Potential factors that influence cognitive complexity were identified and recorded; the review focused on identifying elements affecting the dynamics of an air traffic situation and the sources of patterns in aircraft behaviors.

Methods

Standard Operating Procedures. FAA Order 7110.65 documents general procedures and requirements such as separation standards (FAA, 2004). The order, as well as facility and sector specific standard operating procedures and letters of agreement were reviewed for examples of sources of structure in aircraft trajectories. Documents of the Standard Operating Procedures (SOPs) for three Centers (Boston, Jacksonville, and Washington) as well as the current Letters of Agreement (LOAs) for the Washington and Jacksonville Centers were obtained and reviewed.

The SOPs provide descriptions of each sector in the facility including the predominant flows and points of special interest. Other sector specific structure elements documented include interface procedures, the presence of military or other Special Use Airspace (SUA), sector-specific radio or radar limitations, and holding pattern descriptions. In conjunction with the EMAGE tool, the examination identified some of the consequences of the presence of the structure on typical aircraft trajectories within the sector, the resulting interactions between aircraft, and consequences for the controller's task.

Standard Navigation Procedures. A second part of the review examined standard navigation procedures that are part of the operational environment shared between pilots and controllers. Examples of standard navigation procedures such as Standard Terminal Arrival Routes (STARs), Standard Instrument Departures (SIDs), jet routes and airways were examined. The procedures were evaluated for their impact on the predictability of aircraft trajectories and their implications for the communication of intent between pilots and controllers.

Databases of Airspace Elements. The National Geospatial Intelligence Agency's Digital Aeronautical Flight Information file (DAFIF) was reviewed in order to identify examples of underlying elements of structure. Definitions of sector boundaries were obtained from facility SOP documents and the Aircraft Situation Display for Industry (ASDI) data feed.[14]

Example Results

Airspace Elements. The review of databases of airspace elements identified multiple elements in the operational environment that act as sources of structure observed in the field observations. Examples included navigational airways, SUAs, navigational aid names and locations, fix names and locations, Standard Terminal Arrival Routes (STARs) and published holding patterns; all examples were integrated into the EMAGE tool allowing visualizations to be created of the relationship of traffic flow patterns with structural elements in the current system.

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[14] The ASDI is a real-time feed of the ETMS data described in Section 4.2.1.

Procedures. The review of sector operating procedures identified nine categories of procedures. The categories and examples are shown in Table 10–5 in Appendix III. Two examples of procedures in the form of crossing restrictions are illustrated for the Albany sector in Figure 4–8. The review showed that formal ATC procedures have multiple effects including

- creating tasks (e.g. routing requirements, and crossing altitudes and speeds),
- creating expectations of other controller actions and responsibilities (e.g. control delegation, coordination procedures), and
- standardizing aircraft dynamics (e.g. holding and military training route procedures).

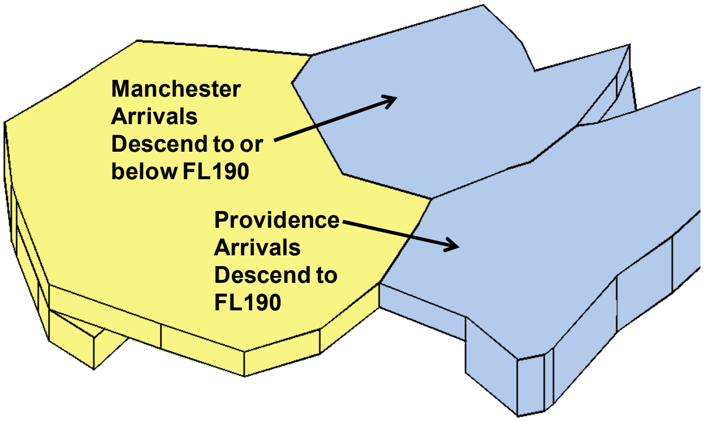

Figure 4–8. Examples of crossing restriction procedures.

4.4 Controller-Pilot Communications

In order to quantitatively investigate the role of structure in commands, a third method used was an examination of controller-pilot communications. Commands by controllers are the outputs of the cognitive processes and hence provide important insights into how structure is used. Previous studies have investigated the correlation of communication loads with controller activity as well as the duration of and frequency of verbal communication events (Manning *et al.*, 2001). Prinzo *et al.* (2007) recently developed complexity metrics of the content of controller-pilot communications in TRACON environments and used them to examine the frequency of readback errors. The analysis used in the current investigation focused on the content of the communications and understanding the role of structure in the implementation of controller commands.

4.4.1 Method

A software application was developed in Microsoft Visual Basic to facilitate the analysis and coding of controller commands. Using the tool, the time, aircraft addressed, and content of each transmission from the controller was captured. In addition, time on frequency was determined by capturing initial "check-in" transmissions from each aircraft. The coding scheme focused on controller–pilot communications; with the exception of the check-in transmissions, pilot-controller communications were not coded. However, pilot-controller communications were used to clarify and interpret controller-pilot communications.

Based on a preliminary sample of the audio data, a coding scheme for the communication events was developed. Each transmission by a controller was reduced to elemental communication events, or the smallest decomposition of parts of a transmission that would retain meaning to the recipient. For example, the transmission "Turn left twenty degrees for spacing" was parsed into the elements of "turn left twenty degrees" and "for spacing."

Elemental communication events were grouped into eight content types that represented general classes of events. Each content type was further subdivided into individual categories (see 0 for a complete listing of coded events and descriptions). Analysis focused on the content type of "commands." Commands were defined as elemental communication events that modified an aircraft's clearance either by requiring or by permitting a modification to the aircraft's trajectory. Based on an initial sample of data, abstract forms of typical commands were identified (see 0). A sample of the resulting output is presented in Figure 4–9. The results of the coding were collected and archived in a Microsoft Access database. This allowed various queries to be developed probing the relative form and frequency of commands and the use of structural references.

```
Time          Aircraft        Communication Event
7:02:24 PM    EAG 834         Discussion <RIDE REPORTS>
7:02:34 PM    EAG 834         Checkout to <ZDC - 133.97>
7:03:22 PM    COM 439         Asked Question: <SAY AIRSPEED>
7:03:33 PM    AAL 705         Checkout to <ZDC - 133.97>
7:03:39 PM    JETLNK 2563     Direct to <VINCE>
```

Figure 4–9 Sample output of coding scheme.

Recordings of two way controller-pilot communications were obtained from two internet websites: www.atcmonitor.com and www.liveatc.net. These websites archive and stream live controller-pilot radio communications using private radio scanners. The use of private scanners created some challenges for ensuring the appropriateness of the data samples. The limitations of line of sight Very High Frequency (VHF) transmissions means some transmissions to / from pilots or controllers may not have been accessible. As well, multiple operators attempting to simultaneously broadcast on a frequency produce a loud squeal significantly reducing the comprehensibility of the transmission. In order to mitigate these challenges, only sectors and data sources known to be broadcasting a single frequency were used.

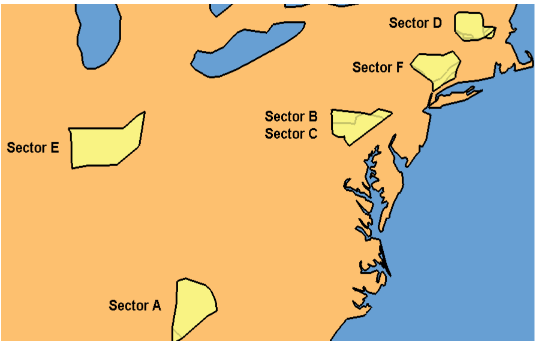

Figure 4–10 **Sectors used to analyze controller-pilot communications.**

Table 4–5. **Altitude ranges of sectors used to analyze controller-pilot communications.**

SECTOR	ALTITUDE RANGE
SECTOR A	**100 – FL 230**
SECTOR B	**FL220 – FL600**
SECTOR C	**900– FL250**
SECTOR D	**Ground – FL230**
SECTOR E	**FL 340 – FL 600**
SECTOR F	**FL 230 – FL 600**

Observations were collected for the six sectors graphical depicted in Figure 4–10.[15] Altitude strata for the sectors are listed in Table 4–5. The sectors were selected to cover a range of operating environments within the set of available data. More than 72 hours of data were analyzed (see Appendix V). Weather conditions in the form of radar images of the general area of each sector were collected in order to support analyses of the effect of convective weather on sector operations. Based on the images, each session was categorized as “convective” or “clear.” The relative difficulty of each sector was compared based on counts of the number of operational errors over the previous 2.5 years in each sector.

In order to support analysis of how communication events varied as a function of the number of aircraft on frequency, the following techniques were developed for determining the number of IFR aircraft on frequency. Aircraft flying under Visual Flight Rules (VFR) and receiving flight following services were excluded based on explicit references, altitudes assigned, and other

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[15] Two sectors located in ZNY are ‘stacked’ one above the other; hence only five of the six sectors are visible in the figure.

relevant data.[16] Repetitions of check in or check out events were recorded; therefore, in general, aircraft were considered on frequency from the earliest check in to the last communication transfer issued by the controller. Cases where it was readily apparent an aircraft had been lost and the controller was 'searching' for the aircraft in an attempt to return it to the correct frequency were eliminated from the analysis.

Approximately 15% of the IFR aircraft were missing one or both of the "check-in" or communication transfer events (e.g. "check outs") used to determine entry and exit times for the aircraft. This included aircraft on frequency at the beginning or end of a continuous block of recordings who would be missing "check-in" and communication transfer events as they would occur before or after the data sample (e.g. "edge effects"). Conservative estimates of the number of aircraft on frequency were developed using two corrections to account for these challenges. In the absence of an explicit "check-in" / "check out" event, the first/last communication event was used as a surrogate "check-in"/"check-out" event. In addition, in order to reduce the impact of "edge effects", the first five and last five minutes of each continuous section of recordings was eliminated from any analysis dependent on the number of aircraft on frequency.

4.4.2 Example Results

Analysis of the coded controller-pilot communication events showed that the proportion of transmissions that were commands was consistently approximately 45% across all sectors (see Figure 4–11). Additional analyses identified the use of structure within, and the relative timing of, controller commands.

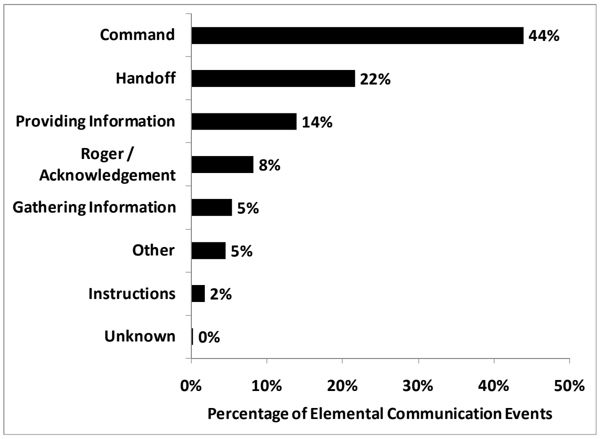

Figure 4–11 Relative frequency of content types.

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[16] Aircraft that checked into a sector at, or climbing or descending to a VFR altitude level (e.g. a "500" foot altitude such as "3,500 feet") were classified as VFR aircraft. Aircraft that entered at a VFR altitude level climbing or descending or receiving a command to climb or descend to an IFR (e.g. a "1,000" foot altitude level)" altitude level were excluded from being classified as VFR. In addition, any aircraft commanded to squawk 1200, "VFR" or instructed to "maintain VFR" were classified as VFR aircraft.

Use of Structure Within Commands. The content of the command events was analyzed for explicit references to elements of structure identified in the review of airspace elements. Extensive use of fix and location references was found in "direct to" and "crossing" restriction commands. For each sector, the relative frequency of these fix and location references was determined, as well as whether the location was internal or external to the sector's lateral boundaries. Figure 4–12 lists the relative frequency of fix/location references used in Sector D as well as whether they were determined to be internal or external to the sector. Five out of six sectors showed a similar pattern of overwhelming dominance by one or two references; as shown in Figure 4–13, for all sectors, at least 20 distinct fix/location references were used.

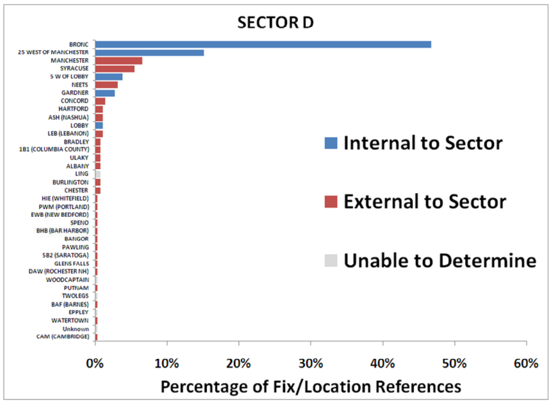


Figure 4–12. **Relative frequency of location / fix references in Sector D.**

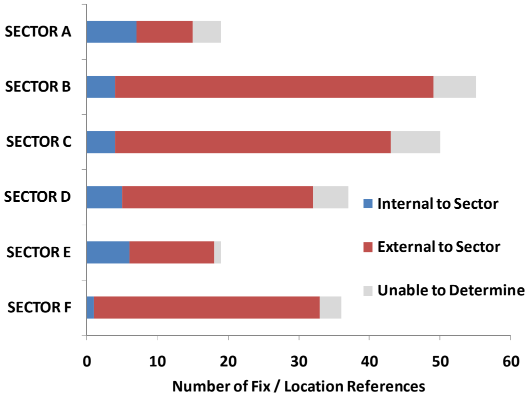


Figure 4–13. **Total fix/location references observed in each sector.**

The locations of the fix/location references were graphically depicted using the EMAGE tool. Figure 4–14 plots the positions of the references for Sector D and illustrates how many of the structural references used in commands are to locations well outside the boundary of the sector.

Timing of Commands. To corroborate the field observations of the timing of controller planning activities, the timing of commands relative to aircraft joining the frequency was determined. As shown in Figure 4–15, analysis of the timing of controller-pilot commands showed over 25% of the commands occur in the first minute after check-in, consistent with the comments

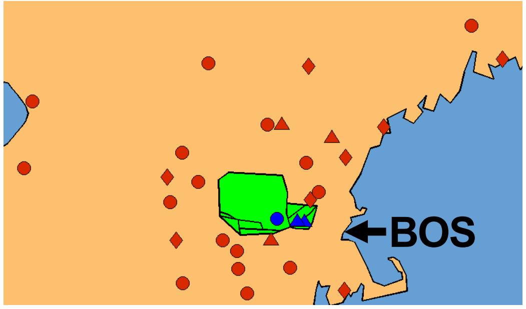
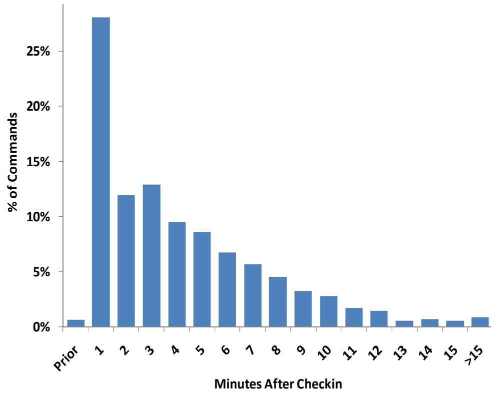


Figure 4–14. **Positions of location references for commands given in Sector D.**

collected during focused interviews and field observations. This pattern was repeated across all sectors analyzed (see Figure 4–16).



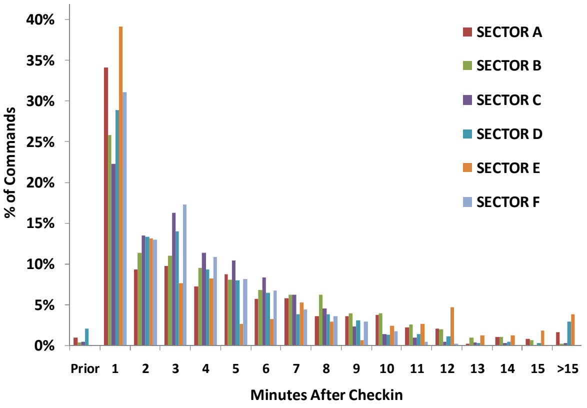
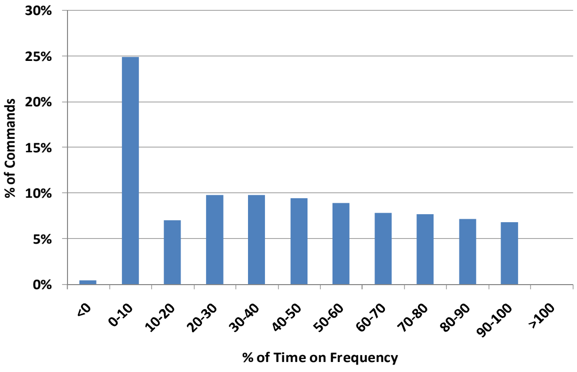


Figure 4–15. Distribution of timing of commands across all sectors.

Figure 4–16. Distribution of timing of commands for individual sectors.

In order to ensure that the effects shown in Figure 4–15 and Figure 4–16 were not due to differences in the sizes and expected time spent in the sectors, a second analysis was performed. For each aircraft, the total time on frequency was divided into 10% bins and the number of commands occurring within each bin was determined. As shown in Figure 4–17 and Figure 4–18, the distribution of timing of commands shows a marked increase in early commands (e.g. within the first 10% of an aircraft's time on frequency), even after accounting for different sector sizes.



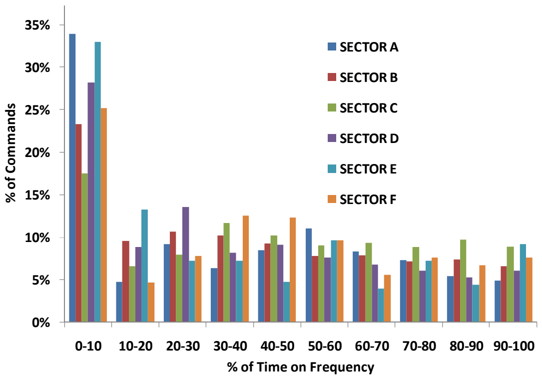


Figure 4–17. Distribution of timing of commands across all sectors.

Figure 4–18. Distribution of timing of commands for individual sectors.

4.5 Chapter Summary

This chapter has described the cognitive ethnographic approach used to identify examples of structure in the ATC operational environment and its potential impact on cognitive complexity. Examples of observations generated by "in situ" observations, analysis of air traffic situations, and commands in controller-pilot communications were presented.

The use of multiple complementary methods provided a unique and valuable way of developing insight into the ATC domain and the influences of structure. For example, a key finding that emerged across all methods was that structure and events beyond the nominal boundaries of the sector are important factors in cognitive complexity. As shown in Figure 4–19, the "Area of Regard" conceptualizes the need to consider structural and complexity influences beyond the physical dimensions of the sector.

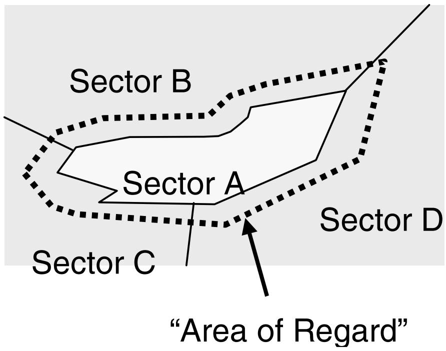


Figure 4–19. "Area of Regard" (dashed line) extends beyond the physical boundaries (solid line) of Sector A.

The "Area of Regard" was particularly observable in sectors with well-defined flows; such sectors tend to have well-defined standard ingress and egress points. In these sectors, field observations showed controllers establishing communications with an aircraft before the aircraft physically enters the sector, or "Area of Responsibility." Analysis of traffic data and transfer of control activities showed that control was often transferred to a "downstream" controller before the aircraft had reached the exit boundary of the sector. Analysis of commands showed the frequent use of references to structural elements beyond a sectors boundaries.

The observations resulting from the methods described in this chapter provided strong evidence that a number of elements of structure appear to be important and play key roles in reducing cognitive complexity. The following chapter identifies these elements of structure and incorporates into the cognitive process model some of their key influences on the operational environment and controller cognitive processes.

CHAPTER 5 Incorporating Structure Into a Cognitive Process Model

The observations and results from the methods described in Chapter 4 showed structure is an important factor in controller mental models and strategies, and hence can have a significant impact on a controller's cognitive complexity. Informed by observations made in the site visits and previous cognitive models in the literature, Section 5.1 presents a cognitive process model describing key cognitive processes and their relationship to cognitive complexity. Section 5.2 of this chapter then describes key elements of structure in the ATC operational environment. Section 5.3 formally incorporates structure and its key influences identified from the *in-situ* observations, traffic situation analyses, and communication analyses into the cognitive process model. The remaining sections of the chapter discuss in detail the key influences of structure in the context of the cognitive process model.

5.1 Cognitive Process Model

In order to provide a framework for understanding potential impacts of structure on cognitive complexity, a simplified cognitive process model was created. The total cognitive space of a controller is very large, encompassing many concepts and processes that may have little or no bearing on the performance of the tasks related to providing ATC services. Thus, the simplified ATC process model focuses on the subset of an air traffic controller's cognitive space that is thought to be specifically related to the task of managing an air traffic situation.

The cognitive process model extends Figure 3–1 by including key parts of Endsley's (1995) model of situation awareness; it also includes the high-level decision making processes previously identified by Pawlak *et al.* (1996). The model is presented in Figure 5–1. As in Endsley's (1995) model, situation awareness supports and influences the controller's decision making process. The result of the decision making process is a "Current Plan" that is the basis for executing actions modifying the operational environment. Changes to the operational environment are perceived, updating the controller's situation awareness, and completing the feedback loop. The following sections describe these key processes in more detail.

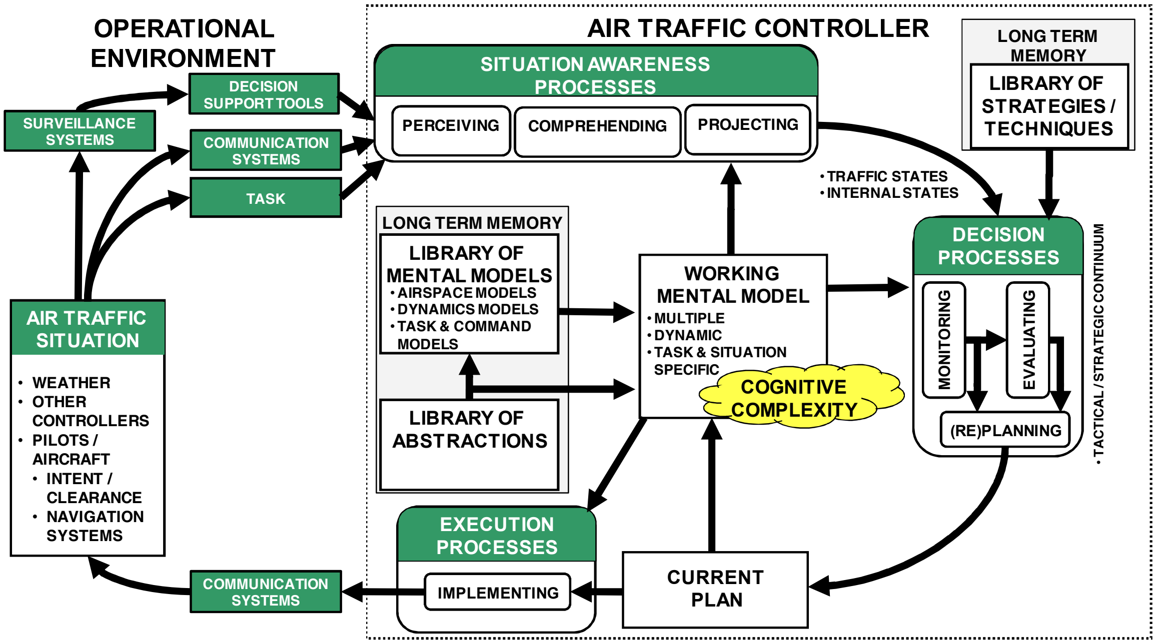


Figure 5–1. Cognitive Process Model.

Situation Awareness

In the model, situation awareness processes of perceiving, comprehending and projecting transform inputs from communication and surveillance systems into inputs to the controller's decision processes. A controller perceives information about current states of the situation, primarily through the auditory and visual modalities. This information is comprehended with respect to the tasks of the controller. Projections of future states of the situation are created using information from the environment in conjunction with the controllers working mental model of the situation.

The situation awareness processes are shown producing awareness of traffic states (e.g. events and objects in the operational environment) and a controller's internal states, such as cognitive complexity, workload, and fatigue. The awareness of these internal states has been shown to contribute to controller evaluation of their own performance and decision making (Kallus *et al.*, 1997).

Decision Processes

A controller's situation awareness is a key input to the decision processes. Integrated into the cognitive process model are four key types of decisions made by air traffic controllers (Pawlak, 1996). Monitoring involves checking the conformance of the current and projected air traffic situations against those expected based on the controller's current plan. Evaluating verifies the effectiveness of the plan in meeting all of the constraints and goals associated with the situation. The monitoring and evaluating decision process can trigger a (re)planning process. In the (re)planning process, a controller identifies and schedules the series of control actions required to ensure the present air traffic situation evolves conflict-free within the constraints associated with the sector.

The model shows the key output from the (re)planning process is a "Current Plan" (Seamster *et al.*, 1993). The "Current Plan" is an internal representation of the schedule of events and commands to be implemented as well as the resulting aircraft trajectories that will ensure that the air traffic situation evolves in an efficient and conflict-free manner.[17] An iteration of the planning process will produce a new schedule of command actions and a new set of trajectories that the controller expects to be conflict free. A controller's "Current Plan" is a complicated store of anticipated actions, timing, and contingencies; like situation awareness, it operates at multiple levels encompassing both expectations of future commands to the system, as well as future selection of strategies and techniques.

The model shows that the "Current Plan" is the basis for implementation of commands that act on the air traffic situation. Executing the plan requires decisions on timing of implementation of specific commands.

The decision processes shown in the model operate on multiple time scales and at different levels ranging from the tactical situation to strategy selection. Based on the multiple outputs from their situation awareness, controllers monitor both the situation and their own resources and capabilities. Choices made at one level impact others; strategies selected in response to anticipated short-term increases in traffic influence immediate tactical decisions. The model captures these different levels by showing the decision-making processes as operating on a tactical/strategic continuum.

Working Mental Model

At the center of the cognitive process model in Figure 5–1 is a controller's working mental model. The working mental model supports the generation and maintenance of situation awareness as well as the various decision-making and implementation processes. Working

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[17] Note that "conflict" is used in the most general sense and could include aircraft-weather, aircraft-airspace and traffic management flow restriction conflicts, in addition to the traditional aircraft-aircraft conflicts.

mental models are a controller's cognitive representation of the system, appropriate for the needs of the current task (Wilson and Rutherford, 1989; Doyle and Ford, 1998; Davison and Hansman, 2003).

The cognitive process model in Figure 5–1 shows the situation specific working mental model is a product of abstractions, mental models and other parts of their long-term memory combined with the controller's "Current Plan." It integrates the various sources of information available to the controller, including perceptual clues of the current positions of aircraft and their future intent, with the controller's long-term knowledge of procedures and the airspace. The working mental model is similar to concepts proposed by Kallus *et al.* (1997). Kallus *et al.* (1997) described "mental pictures" as "moment- to-moment snapshots of the actual situation based on the mental model and the actually perceived external cues" and noted that the generalization of these mental pictures is "sometimes defined as more general mental models" (Kalus *et al.*, 1997, Pg. 11).

Long-term Memory

Abstractions, as well as mental models and strategies and techniques, are shown in the model as components of a controller's long-term memory. In the model, the knowledge maintained in long-term memory is shown grouped into distinct libraries.

Library of Mental Models

The term mental models is typically used in the literature to describe stable frameworks or models of a system that are retained in long-term memory (Kalus *et al.*, 1997, Pg. 30). Mental models incorporate the controller's understanding of the structure of the system being controlled as well as the dynamics of the air traffic situation (Kerstholt and Raaijmakers, 1997, Pg. 213).

The library of mental models contains a controller's knowledge of their airspace (airspace models), models of the dynamics of both aircraft and parts of the operational environment such as thunderstorms and wind patterns, as well as models of their tasks and the control mechanisms available to perform those tasks.

Library of Abstractions

Abstractions simplifying these mental models are shown in the Library of Abstractions. By drawing from the Library of Abstractions, controllers can simplify both the mental models in long term memory and the dynamic, situation and task-specific, working mental model.

Library of Strategies / Techniques

The model also shows long-term memory containing a library of strategies and techniques, reflecting a controller's knowledge of how to perform tasks. Strategies and techniques are domain or airspace specific approaches to performing a task. The library of strategies and techniques is retained in the same long term memory as the previously described libraries but is shown separately in the interests of graphical clarity as they primarily affect a controller's decision processes. A controller's strategies and techniques are developed over time from experience and through training processes.

Strategies and techniques help controllers narrow the range of possible command actions. Aircraft can be turned, climbed, sped up, slowed down or complex combinations thereof. In many cases, the trajectory of more than one aircraft could be altered in order to successfully perform the task. Many different strategies for controlling traffic can be used successfully (Cardosi and Murphy, 1995) and the strategies that are appropriate may depend on a variety of external factors including weather and airspace.

5.2 Structure in Air Traffic Control

The observations and results from the methods in Chapter 4 were used to identify examples of structure. For the purposes of this thesis, structure was defined as the physical and information elements that organize and arrange the ATC environment. Multiple examples of elements of structure were identified using the methods described in Chapter 4.

Airspace maps capture and depict many of the core elements of structure. Figure 5–2 shows an example of a simplified version of the airspace map for a low-level sector near Jackson, Mississippi. Examples of elements of structure shown on the map include:

- navigation fixes such as intersections (triangles),
- lateral paths such as airways and jet routes,
- airspace boundaries, and
- minimum altitudes.

Each of these elements contributes to the organization and arrangement of the ATC environment. Intersections are navigated to / from, directly contributing to the dynamics of an aircraft. In other cases, such as airspace boundaries or minimum altitudes, the structure determines where those dynamics occur.

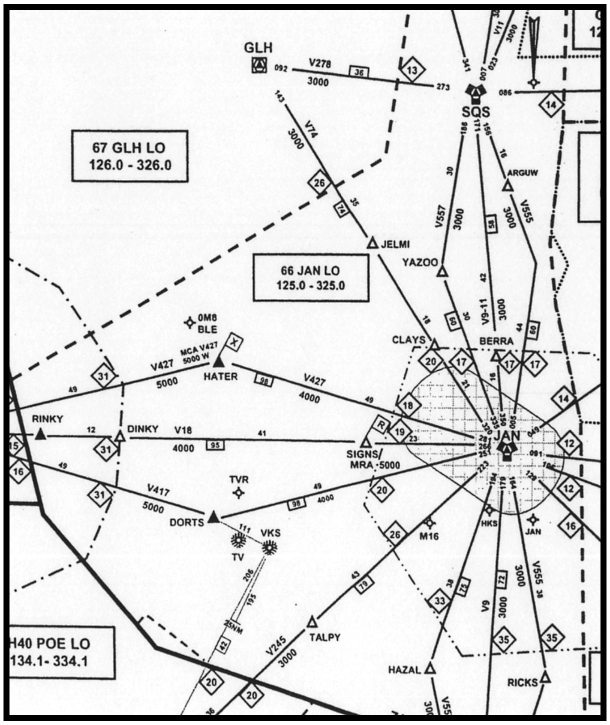


Figure 5–2. Simplified airspace map.

Other examples of airspace structure were standard operating procedures and sector-specific operating procedures (Section 4.3.2). Procedures set out rules and requirements for aircraft trajectories and/or controller actions, thereby contributing to the dynamics of the air traffic situation.

Many of the examples of structure identified in the observations were dependent on other structural elements. For example, the spatial path of airway and jet routes are formally defined by the locations of navigation fixes such as Very High Frequency Omni-directional Radio Ranges (VORs) and intersections to define the spatial path. The physical locations of VORs, in turn, depend on terrain and other characteristics of the environment.

Based on the identified examples, three distinct types of structure were identified. The distinct types were incorporated into a hierarchical framework reflecting the dependencies between different elements of structure. The different types of structure correspond to the high-level layers of the hierarchy shown in Figure 5–3: patterns, procedures, and framework. Each high-level layer is comprised of several sub-layers; for example, the procedures layer is shown with sub-layers of published procedures and ATC procedures. Each sub-layer contains examples of generalized classes of structural elements and examples of specific structural elements. For example, the published procedures sub-layer includes generalized classes of communication protocols, trajectory procedures and regulations.

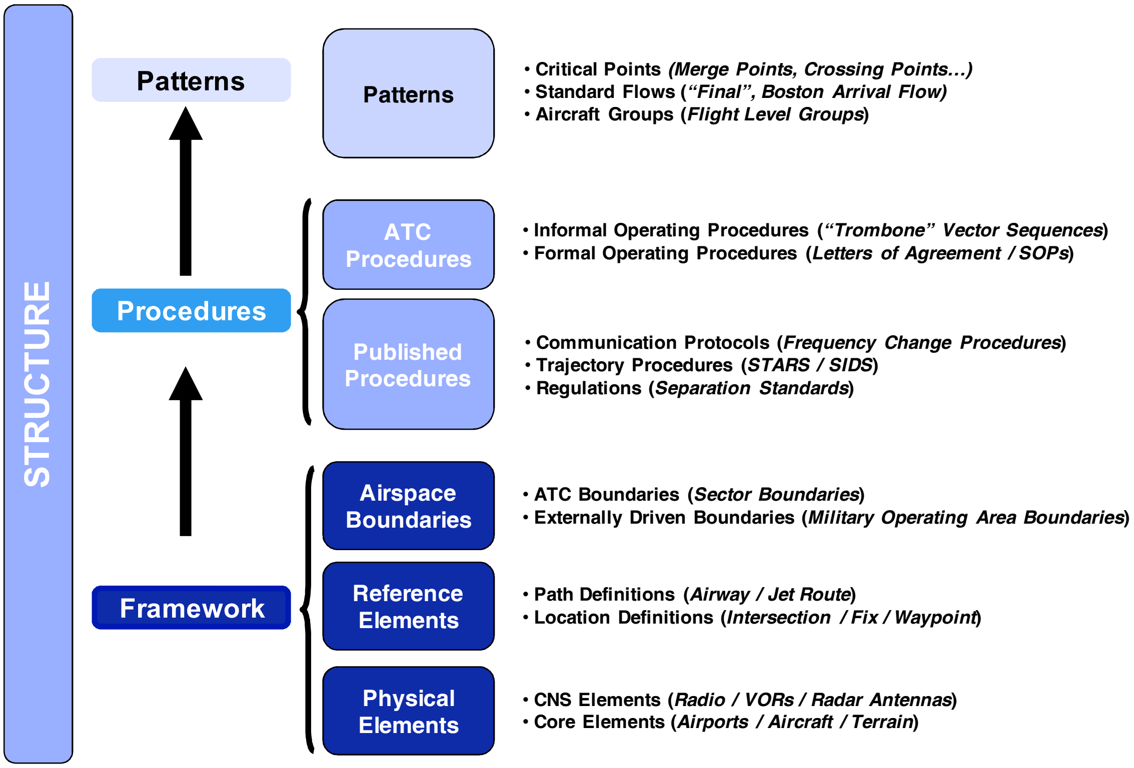
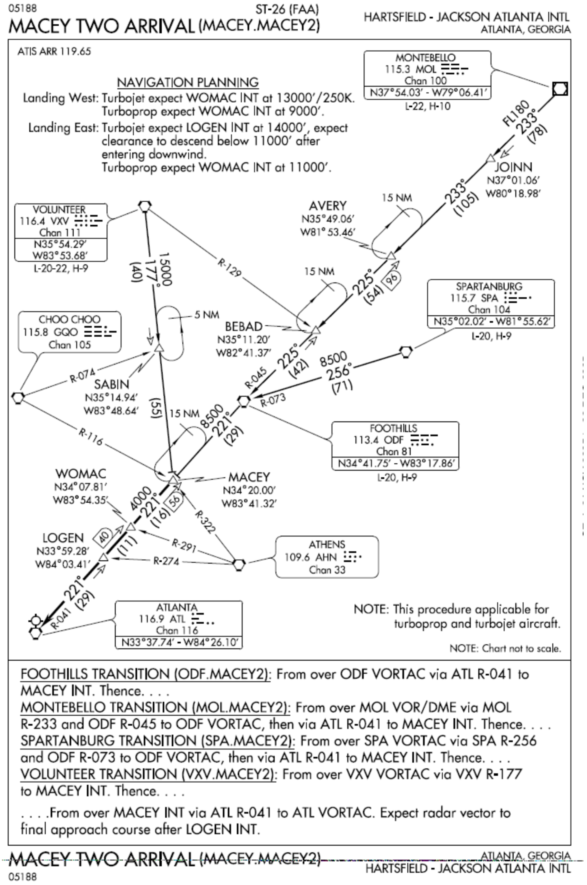


Figure 5–3. Structure hierarchy.

At the base level of the hierarchy is the framework layer of structure. The framework layer is comprised of sub-layers that contain elements establishing the foundation and context of an air traffic situation. Framework sub-layers include physical elements, reference elements and airspace boundaries.

Physical elements are the physical infrastructure of the system including airports, as well as the physical communication, navigation, and surveillance infrastructure such as radio or VOR antennas. Historically, physical elements have been the basis of reference elements, or the fixes, waypoints, airways and jet routes that provide common, shared, and easily communicated definitions of altitudes, locations, and lateral paths. Airspace boundaries, including sector boundaries, are typically defined relative to the reference elements. Other boundaries such as definitions of Special Use Airspace, are also examples of airspace boundaries.

In the middle of the hierarchy is the procedure layer. Structural elements in the procedure layer build on the context created by the framework layers. Published procedures include procedures that define aircraft trajectories such as Standard Instrument Departures (SIDs) and Standard Terminal Arrival Routes (STARs). An example of a STAR for arrivals to Atlanta from the North East is shown in Figure 5–4. As can be seen in the figure, trajectory procedures use elements defined in the reference elements sub-layer and add additional constraints to create shared definitions of expected lateral, longitudinal (e.g. speed) and/or vertical paths. For example, the STAR in Figure 5–4 uses reference elements such as the MACEY and LOGEN fixes to define the lateral path of aircraft.



NAVIGATION PLANNING

Landing West: Turbojet expect WOMAC INT at 13000'/250K.
Turboprop expect WOMAC INT at 9000'.

Landing East: Turbojet expect LOGEN INT at 14000', expect clearance to descend below 11000' after entering downwind.
Turboprop expect WOMAC INT at 11000'.

NOTE: This procedure applicable for turboprop and turbojet aircraft.

NOTE: Chart not to scale.

FOOTHILLS TRANSITION (ODF.MACEY2): From over ODF VORTAC via ATL R-041 to MACEY INT. Thence. . . .
MONTEBELLO TRANSITION (MOL.MACEY2): From over MOL VOR/DME via MOL R-233 and ODF R-045 to ODF VORTAC, then via ATL R-041 to MACEY INT. Thence. . . .
SPARTANBURG TRANSITION (SPA.MACEY2): From over SPA VORTAC via SPA R-256 and ODF R-073 to ODF VORTAC, then via ATL R-041 to MACEY INT. Thence. . . .
VOLUNTEER TRANSITION (VXV.MACEY2): From over VXV VORTAC via VXV R-177 to MACEY INT. Thence. . . .

. . . .From over MACEY INT via ATL R-041 to ATL VORTAC. Expect radar vector to final approach course after LOGEN INT.

Figure 5–4. MACEY TWO standard terminal arrival.

A second procedure layer captures internal ATC procedures. Formal procedures include the Standard Operating Procedures (SOPs) and Letters of Agreement (LOAs) that govern the behavior of traffic at the interfaces between sectors. SOPs document the entry and exit procedures for each sector. The interface procedures between sector 22 in Boston Center and the surrounding high altitude sectors are shown in Figure 5–5. The procedure layer also includes informal operating procedures; during the field observations controllers were observed following undocumented, or informal, procedures that imposed structure directly on air traffic situations. Structure was observed being imposed directly by controllers. For example, during observations of the "Final" position at the Boston TRACON, controllers repeatedly issued commands producing "downwind", "base" and "final" legs consistent with standard "trombone" vectoring patterns.

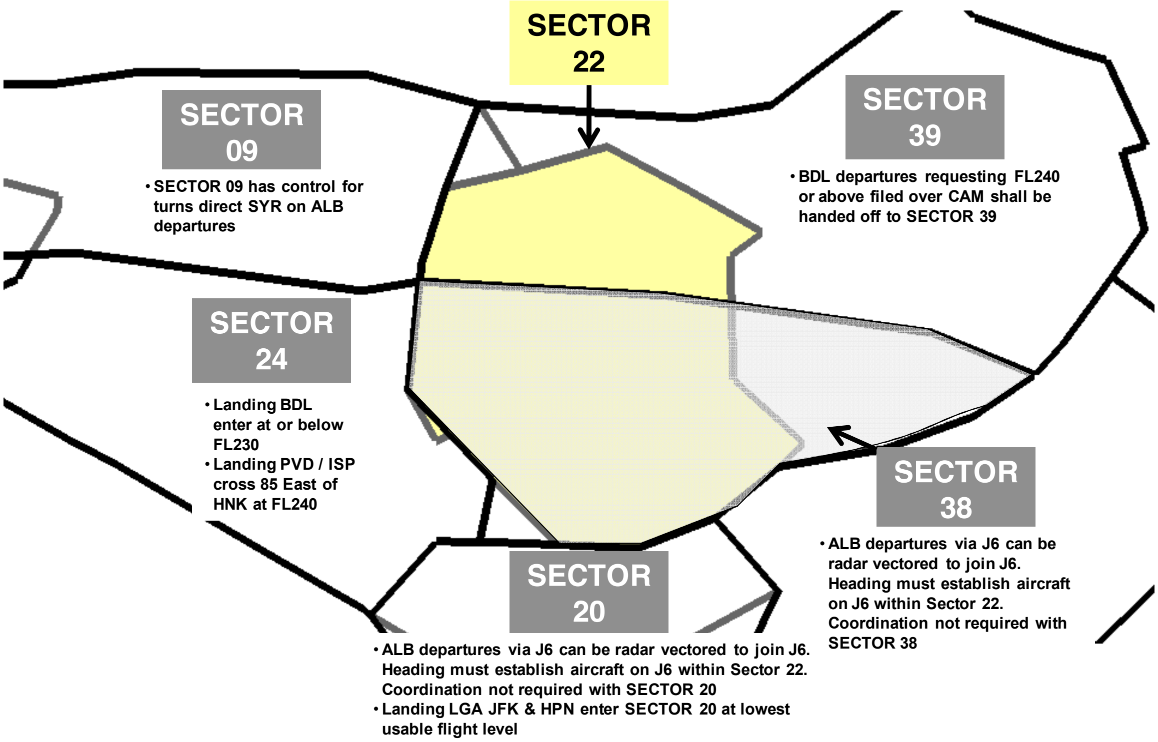


Figure 5–5. Interface procedures with high altitude sectors above Boston Center's Albany Sector (Sector 22).

The elements within the framework and procedure layers are a core source of the top-most layer of structure: the patterns of aircraft behavior. Several examples of important structural patterns in aircraft behavior were identified. Three key elements are standard flows, critical points, and aircraft groups.

During the focused interviews and field observations, controllers identified the standard flows of aircraft through a sector as a key structural feature of the sector. Visualizations of the density of 24 hours of traffic for more than 30 sectors showed most sectors have one or more standard flows. Figure 5–6 depicts the eastbound standard flows through high altitude sectors in Cleveland Center. The dependencies between the thick lines showing standard flows (pattern layer structure) and the thin lines representing the jet routes (framework layer structure) is evident in Figure 5–6.

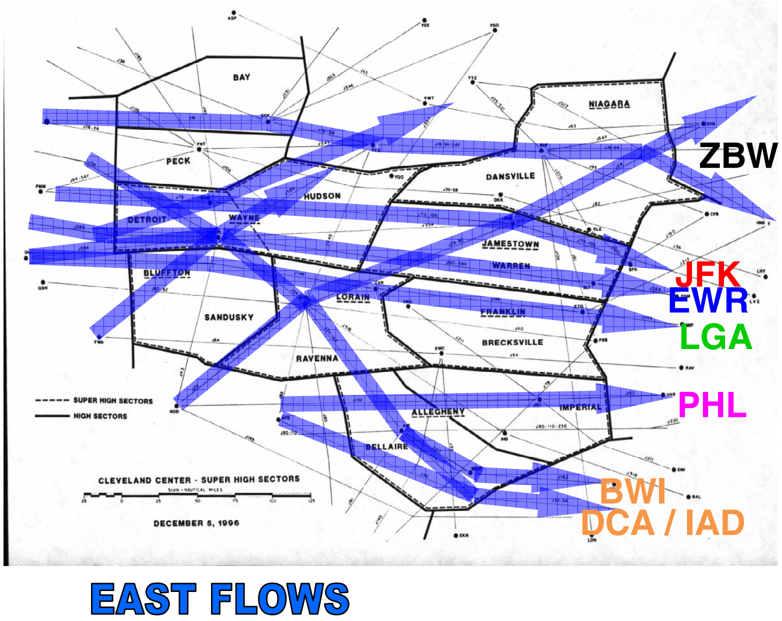


Figure 5–6. **Eastbound standard flows (thick, dark lines) through Cleveland Center airspace. (Image courtesy Cleveland Center Traffic Management Unit).**

A second key example of structure in the pattern layer is locations with high concentrations of traffic, or critical points. The effect of lower layers of structure is to concentrate traffic over common locations such as crossing points and merge points. Four examples of critical points are circled in Figure 5–7.

Figure 5–7. **Critical points in Sector 22, Boston Center.**

Pattern layer structure also includes patterns found in the form of groups of aircraft. Groups can be a product of the spatial proximity of aircraft or common performance characteristics. Groups were observed being used during convective weather events, as large numbers of aircraft are shifted between arrival fixes (see Figure 5–8). Common sources of dynamics, such as similar power-to-weight ratios, or shared company operating procedures also form groups of aircraft.

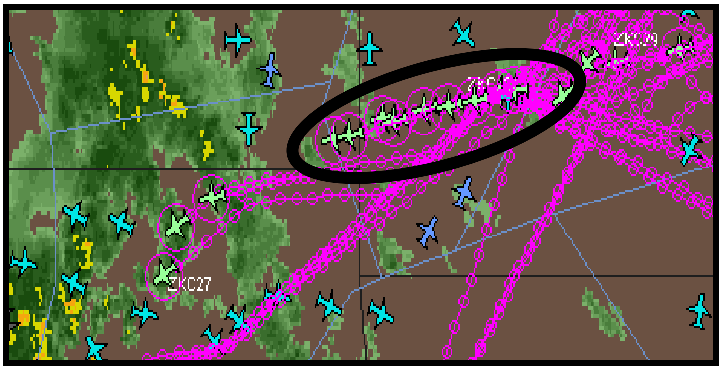


Figure 5–8. Circle highlights group of aircraft rerouted during convective weather event. (Image courtesy ***Flight Explorer***)

The structure hierarchy summarizes the elements of structure in the operational environment and the relationships between different elements. It provides a useful tool for identifying and understanding the full range of effects that changes to one element of structure can have. Understanding all of the consequences that changes to structure can have is particularly important as observations suggested that structure has multiple influences on cognitive complexity. The following sections describe key influences of structure and its formal incorporation into a cognitive process model.

5.3 Incorporating Structure into the Cognitive Process Model

The observations showed that structure is an important factor in the sources of cognitive complexity and the strategies used to reduce cognitive complexity. The cognitive process model presented above was modified to explicitly incorporate structure. In the modified model, shown in Figure 5–9, the high level layers of the structure hierarchy are shown as a distinct part of the operational environment.

Having identified the importance of structure, the modified model was used as a framework for identifying potential influences of structure for controller cognitive complexity. Using the modified model, and informed by the observations, five primary mechanisms by which structure influences cognitive complexity were identified and are incorporated into the modified cognitive process model in Figure 5–9.

The cognitive process model is parsed into the operational environment and the controller's cognitive processes. Section 5.4 first discusses the identified influences on the operational environment. Section 5.5 then describes influences of structure on the cognitive processes in the model.

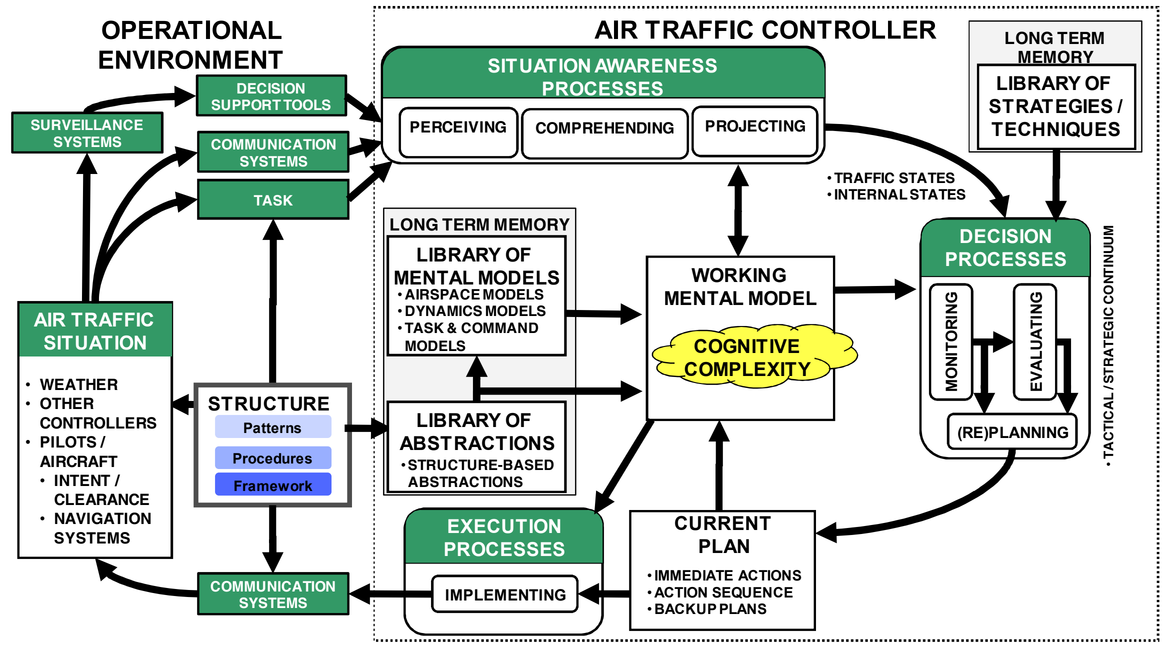


Figure 5–9. **Modified cognitive process model explicitly incorporating influences of structure.**

5.4 Influences of Structure on ATC Operational Environment in Cognitive Process Model

Figure 5–10 reproduces Figure 5–9 highlighting the influences of structure on the operational environment. Structure influences the air traffic situation and its dynamics, the task, and the commands issued through the communication system. The following sections discuss each of these influences separately.

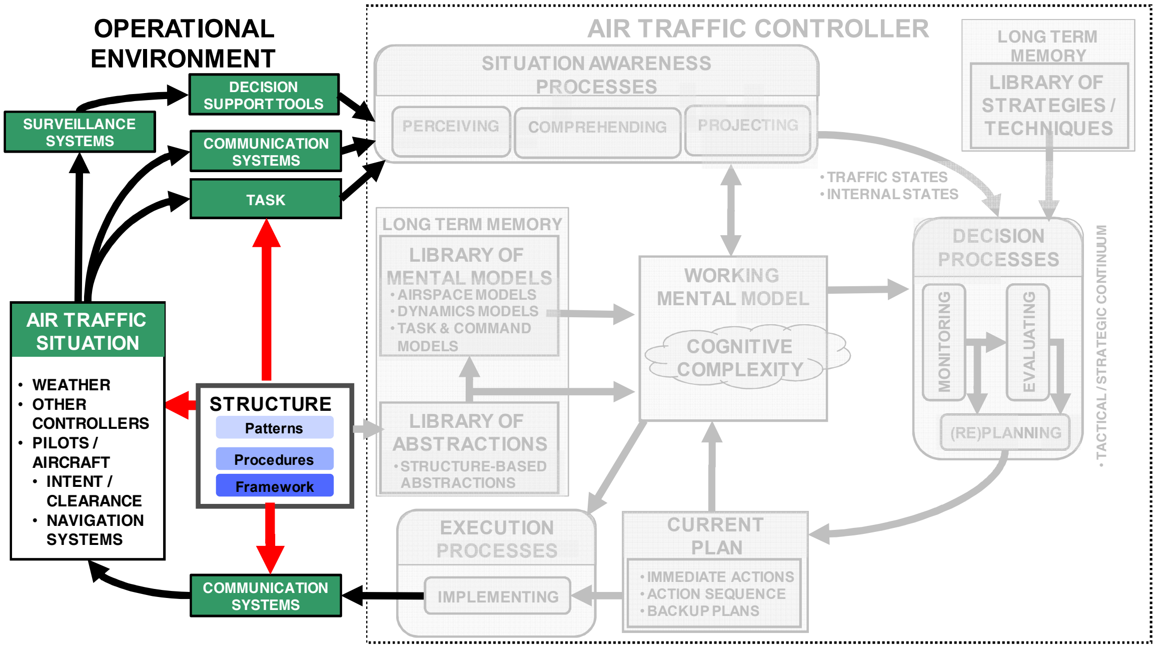


Figure 5–10. **Modified cognitive process model highlighting influences of structure on operational environment.**

5.4.1 Structure's Influence on the Air Traffic Situation

A key influence of structure is its impact on the air traffic situation and its dynamics. The presence of structure acts to limit the dynamics of aircraft by imposing constraints on the possible future states of an aircraft. These constraints act as rules or principles establishing, in part, the underlying physics of the operational environment. This influence was included in the model in Figure 5–10 by showing structure directly influencing the air traffic situation.

Figure 5–11 illustrates this effect. In Figure 5–11, the aircraft identified as "EGF547" is tracking the jet route "J547". Under nominal conditions, and in the absence of further input from the controller, the jet route determines the future trajectory and positions of the aircraft. Jet routes are only one example of the many elements of structure that influence an aircraft's dynamics. Elements such as airways, fixes, and procedures such as Standard Terminal Arrival Routes (STARs) are means of specifying trajectories that aircraft attempt to conform to, creating aircraft dynamics and behavior that is consistent with the structure.

Figure 5–11. Aircraft tracking jet route J547.

The dynamics of the air traffic situation are also influenced by procedures and airspace boundaries that segregate aircraft based on their performance characteristics. The segregation of operations both reduces variability in the dynamics of aircraft as well as puts limits on where those dynamics occur. Procedures and airspace boundaries restrict access to some parts of the airspace to those aircraft that can meet minimum performance standards. This has the effect of standardizing the dynamics in the resulting subparts of the air traffic situation.

Two examples illustrate the point. Procedures creating separate arrival flows for turboprops and jets segregate aircraft with different speeds and descent rates, standardizing the dynamics of aircraft within each arrival flow. Boundaries such as Military Operating Areas (MOAs) and other examples of Special Use Airspace (SUA) segregate the distinct dynamics of high-performance military aircraft from commercial aircraft. Additionally, the boundaries limit the airspace where those dynamics occur; as shown in Figure 5–12, SUAs (red polygons) in the western United States heavily restrict where commercial aircraft can fly. Figure 5–12 shows both actual tracks flown (magenta) and filed flight plans (black) are constrained by the boundaries of the military airspace.

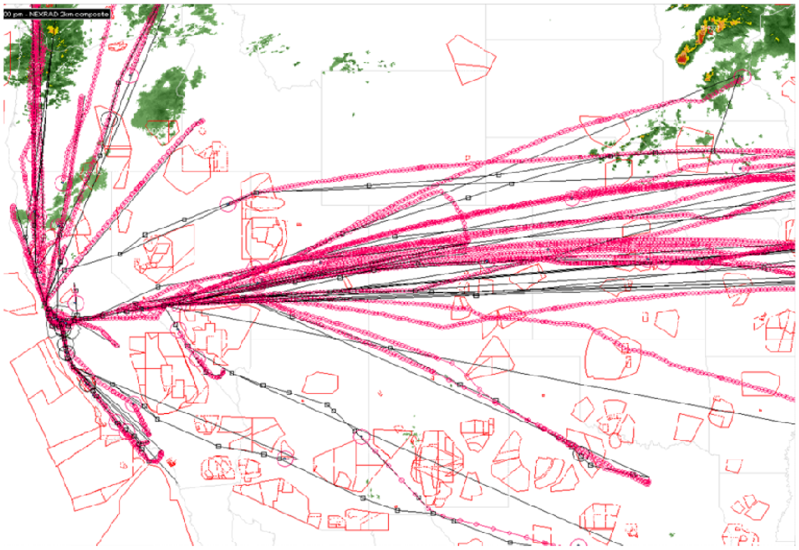


Figure 5–12. Special Use Airspace (red) influences dynamics of aircraft destined San Francisco.

Finally, structure directly influences the dynamics of an air traffic situation by minimizing the impact of disturbances in the environment. Aircraft following similar lateral and/or vertical trajectories will be exposed to similar effects from disturbances such as the relative wind. This minimizes the differential effect of such disturbances on the aircraft dynamics.

5.4.2 Structure's Influence on the Task

Structure's influence on the task comes in multiple forms, ranging from limiting the spatial and temporal scope of responsibility, to creating and removing tasks. These influences were incorporated into the modified cognitive process model by showing a direct relationship between structure and the controller's task.

A key influence of structure on the task is its role in limiting the scope of a controller's responsibility, both spatially and temporally. Sector boundaries create lateral and vertical bounds on the aircraft being controlled. Figure 5–13 illustrates the distinction between aircraft under the control of a sector, and those outside of it; aircraft within the sector are shown in bold, with full data blocks, whereas aircraft outside the sector are shown in grey, with partial data blocks.[18]

The sector boundaries decompose tasks between controllers and limit the number of aircraft under control. In addition, the boundaries provide limits on the temporal horizon of tasks such as conflict detection and resolution. In Figure 5–13, events that occur far into the future, when the aircraft are well beyond the sector boundary, do not form part of the controller's task. However, as discussed in Chapter 4, the sector boundaries are not a strict delineation of the controller's task. Observations of controller actions and commands showed that the effective scope of a controller's task, or Area of Regard, is consistent with and extends beyond the formal boundaries of the sector.

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[18] Data blocks are the information tag associated with each aircraft. See Chapter 3, Section 3.4.1.

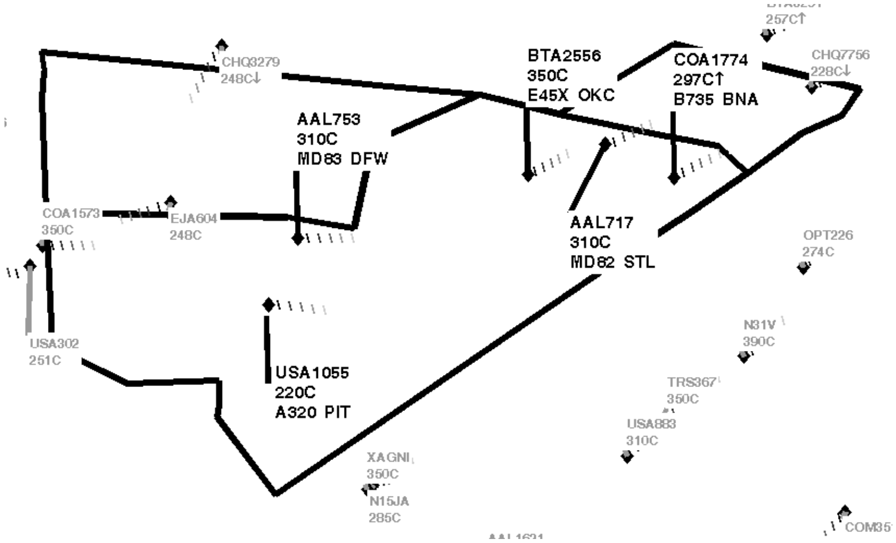

Figure 5–13. Sector boundaries limit spatial and temporal scope of controller's task.

Structure also influences the task through the offloading of tasks from the controller. Structure offloads tasks by preventing situations that would require controller intervention from occurring. In essence, structure pre-solves parts of the task and introduces an independence between aircraft in the situation. For example, the use of minimally separated discrete altitudes creates structure in the vertical domain (Section 4.3.1). This offloads conflict detection tasks from the controller by eliminating the potential for conflict between aircraft at different altitudes.

The flows in an airspace can also offload tasks. This similarly transforms the controller's task by creating segregated, independent, parts of the situation through procedural deconfliction. For example, separated standard arrival and departure routings can eliminate intersections between aircraft flight paths, removing the potential for conflicts between aircraft.

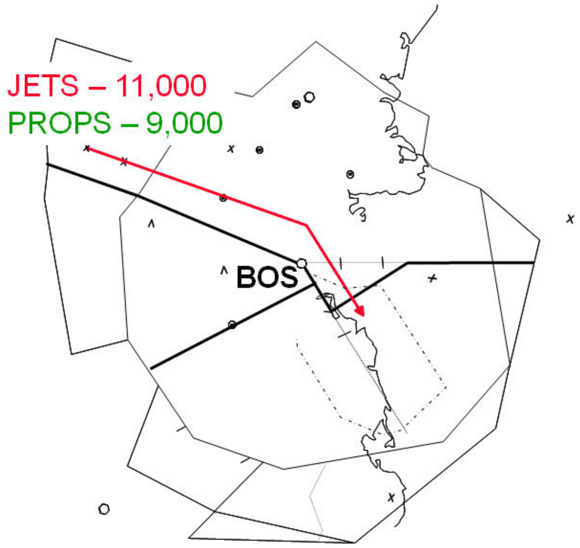

Figure 5–14. **Altitude segregated arrival flows to Boston (BOS) through the Rockport Sector in the Boston TRACON.**

Structure also creates tasks for controllers. Controllers must ensure that aircraft meet the requirements of procedures, such as crossing restrictions at a sector boundary. For the controller supplying aircraft at the boundary, the procedure creates the task of establishing the aircraft at the correct altitude.

The multiple influences of structure on the task often influence the task for more than one controller. Figure 5–14 depicts arrival routings and altitudes for turbo-prop and jet aircraft arriving from the northwest and passing through the Rockport sector in the Boston TRACON. An interface procedure segregates faster jet aircraft (at 11,000 feet) above slower turboprop arrivals (at 9,000 feet) eliminating the possibility of fast overtakes from the Rockport controller's task. However, for the controller supplying aircraft to the Rockport sector, the procedure creates the task of meeting the altitude restrictions at the sector exit boundary.

5.4.3 Structure's Influence on Commands and Communications

The commands used by controllers to modify how the air traffic situation evolves are influenced by structure. Structure provides a language and set of references that are used to communicate intent. These influences are captured in the model Figure 5–10 as structure impacting the communication systems on the command path used to implement the controller's "Current Plan."

Many of the commands that are used by controllers to modify aircraft clearances explicitly use or reference the airspace structure, particularly reference layer elements. Controllers routinely clear aircraft to fly "direct" to a navigational fix; navigational fixes can be defined by VORs, waypoints, or intersections. Figure 5–15 shows an aircraft that had been following jet route "J80" flying directly to an intersection, VINSE, beyond the sector boundary. This command was frequently observed during the communication analysis of the sector in Figure 5–15. The presence of the VINSE intersection provides a simple, quickly implementable means of granting and communicating a "shortcut."

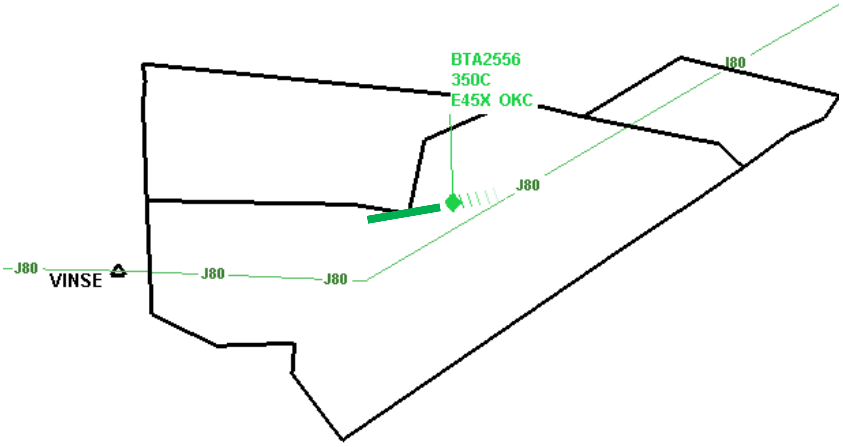

Figure 5–15. Navigation fixes used to give "direct to" clearances.

The elements of structure provide compact and efficient means of expressing complicated trajectories. Published holding procedures encapsulate details of aircraft turn directions, navigation equipment frequencies and other details that are time consuming to broadcast to aircraft. As expressed by one controller, "Published holding [is] simple. [The] entrances are easier – cleared as published. Reduces amount of info have to convey."[19] Jet routes, or procedures such as a Standard Terminal Arrival Route (STAR), allow a controller to produce multiple trajectory changes with a single instruction. These procedures give guidance to both pilots and controllers on complicated three-dimensional trajectories with specific limitations on and/or expectations of aircraft altitudes and speeds.

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[19] October 20, 2001, Cleveland Center, Air Traffic Controller

For example, the BUNTS ONE STAR, shown in Figure 5–16, has multiple lateral turns and conveys altitude and speed expectations. An aircraft cleared to fly the BUNTS ONE arrival procedure will make the series of turns (circled) between the Phillipsburg VOR and BUNTS intersection without further input from the controller. The turns may be necessary for any of a number of reasons including segregating the arriving aircraft from other aircraft flows, special use airspace, or the limitations of current navigation systems. The STAR is a powerful tool that a controller can use to concisely implement a complicated trajectory and communicate expectations and intent to pilots.

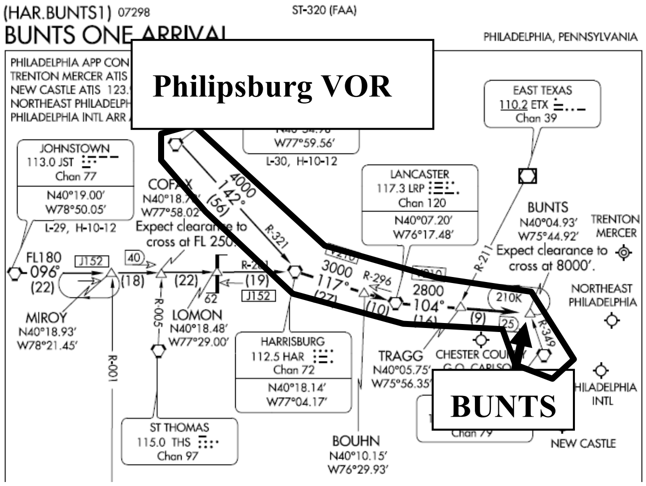

Figure 5–16. "Cleared BUNTS ONE arrival" concisely communicates multiple, complicated, trajectory changes for aircraft destined Philadelphia.

5.4.4 Additional Influences on Operational Environment

Additional influences of structure on the operational environment were observed. The influences are similar to those described above, and therefore, for the purposes of maintaining clarity of the model in Figure 5–9 have not been explicitly depicted.

Physical structure, in the form of terrain and the physical locations of radar transmitters and receivers, influences the performance of surveillance systems. This determines the applicable separation standards, influencing the controller's task.

In addition to influencing the commands used by controllers, structure plays a role in the communications received from pilots and other controllers. Pilots use structural references to express desired reroutes, or deviation paths around weather. Controller-controller communications often require a controller to specify where the receiving controller needs to look on their radar screen for an aircraft being pointed out. As the two controllers are often in separate buildings, or otherwise unable to view each other's screen, having a set of shared, commonly understood reference points is an important means of ensuring effective and efficient communications between the controllers.

5.5 Influences of Structure on Cognitive Processes in Cognitive Process Model

Structure in the operational environment also influences controller cognitive processes. Observations suggest this influence is primarily through the controller's working mental model (WMM), and the strategies and techniques used in core decision processes. The controller's working mental model, strategies, and techniques take advantage of controller knowledge of the structure in a sector and its influences on the operational environment discussed above. This knowledge is developed through training and experience and is retained in long-term memory. It enables controllers to use simpler working mental models; strategies and techniques also take advantage of knowledge of the influences of structure on the operational environment.

The modified cognitive process model, repeated in Figure 5–17 with the cognitive processes highlighted, explicitly shows a relationship between structure and a controller's long-term memory. The following sections discuss the key influences of this knowledge on a controller's working mental model and a controller's strategies and techniques.

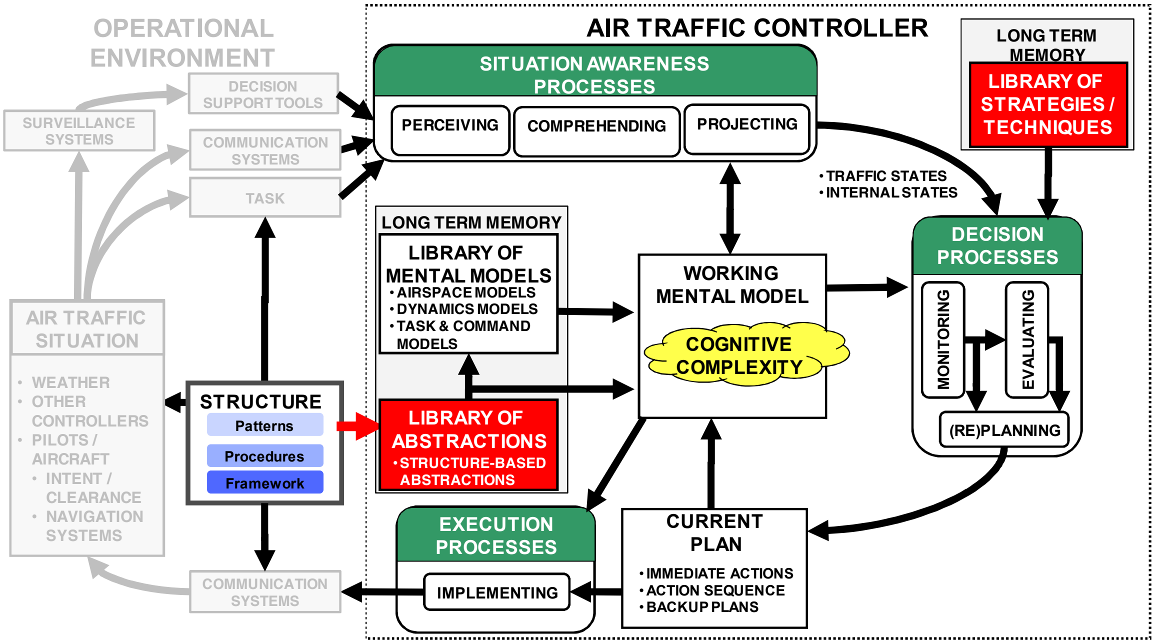

Figure 5–17. Structure's influence on cognitive processes.

5.5.1 Structure's Influence on Controller Working Mental Models

Structure influences the working mental model by providing a basis for simplifying abstractions. Such abstractions, shown as structure-based abstractions in Figure 5–17, are generalizations used in a working mental model. Based on one or more elements of structure in an air traffic situation, structure-based abstractions are a controller's internalization of the influences of that structure on the dynamics of an air traffic situation, on available commands and the task. Multiple structure-based abstractions can be present in a working mental model, and the particular use of a structure-based abstraction will be task and goal specific.

Structure-based abstractions are a key link between the influences of structure on the operational environment, and the reduction of cognitive complexity. They allow controllers to use working mental models that are as effective as, but less cognitively demanding than, detailed representations of an air traffic situation. By incorporating known effects of structure, simpler, less detailed, and standardized dynamics of an air traffic situation can be used, simplifying the working mental model, while still maintaining the level of performance appropriate for their current task.[20]

Unrecognized, the influences of structure on the operational environment would have no consequences for a controller's cognitive complexity. Controllers, such as trainees, that are not aware of, or lack knowledge of, the underlying structure and its influences are faced with what appear to them to be more intricate tasks, requiring aircraft specific models of dynamics, and more frequent and difficult command interventions. As a simple example, structure that "pre-solves" the task, such as separate flows for arriving and departing traffic can only reduce cognitive complexity if the segregation between those flows is recognized and incorporated into the controller's working mental model.

Structure-based abstractions are cognitively powerful ways of simplifying the working mental model. There are multiple mechanisms by which they simplify a working mental model. A controller can use structure-based abstractions to decompose their task. As discussed above, the presence of structure pre-solves tasks and segregates parts of an air traffic situation. Abstractions recognizing the resulting independence between aircraft simplify the working mental model by suppressing aircraft and relationships that are not important for the current task.

Structure-based abstractions also simplify a working mental model by reducing the "order" of the working mental model. The order of a model is defined as a notional property reflecting the degrees-of-freedom required to project future behavior of the situation. Parameters or states that

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[20] Such an approach may be considered analogous to Physicists modeling a gas as a singular system with aggregate properties such as Volume and Pressure, despite the gas being composed of numerous individual particles.

are required to accurately model how relationships between aircraft will evolve increase the degrees-of-freedom. A working mental model that represents an air traffic situation as a large multi-dimensional search space, e.g. one with high degrees-of-freedom, can be cognitively very difficult to evaluate, particularly when the dimensions are interdependent. For example, evaluating a situation where vertical separation *might* exist is more challenging than evaluating one where it is explicitly known *not* to exist (Fields *et al.*, 1998).

Structure's affects on relative aircraft dynamics reduces the number of unique degrees-of-freedom required to model a situation. For example, arranging aircraft in a standard flow reduces the number of degrees of freedom that must be modeled in order to project distances between aircraft at points in the future. This simplifies projection and evaluation of relationships.

Models with a high degree-of-freedom can be a powerful and accurate representation of the real world but require greater cognitive resources (e.g. memory, time). A high number of degrees-of-freedom may be necessary to track complicated dependencies and interactions in the environment. For example, "turning aircraft C to avoid the conflict with aircraft B would induce a conflict with aircraft D." (see Figure 5–18). However, as they reflect the influences of structure on the task, structure-based abstractions allow controllers to shrink the number of dimensions in their working mental model and recognize the elimination of interactions between those dimensions. Procedures establishing distinct altitudes based on direction of flight introduce altitude separation between aircraft C and D in Figure 5–18. A structure-based abstraction based on this procedure layer structure would allow a controller to use a simpler working mental model that accounts for this "presolving" when resolving the original conflict.

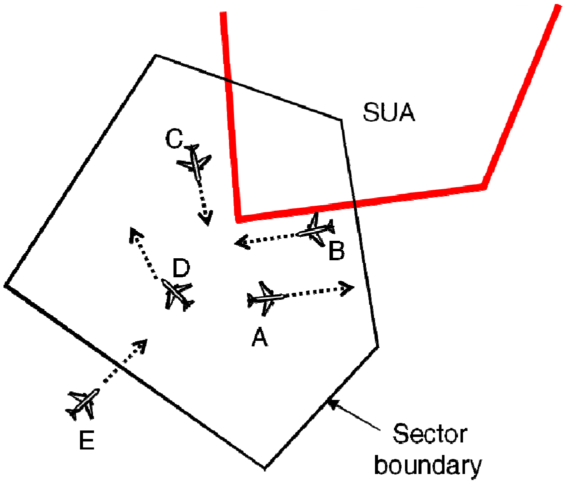

Figure 5–18. **Working mental models can required to be of high order to appropriately capture complicated dependencies amongst a set of aircraft.**

Structure-based abstractions also simplify evaluating and (re)planning processes by capturing pattern layer structure that can be used as part of the recognition-primed decision making processes described in Section 5.1. Such abstractions enable rapid categorization and prioritization of aircraft in the situation and support decompositions of situations into standard and non-standard aircraft (Section 4.2.2). This enables more rapid recognition of potential problems and previously used resolution actions. For example, standard problems and resolution actions are associated with standard aircraft in a sector. This is significantly easier than detailed evaluation and consideration of all possible problems and potential resolution actions.

Finally, structure-based abstractions provide efficient means of ensuring a controller's "Current Plan" is consistent with the available command mechanisms. Such abstractions incorporate the complicated trajectories enabled by procedures, simplifying the process of determining what resolution maneuvers are possible. In addition, structure-based abstractions can also be used as the basis of the controller's current plan, reflecting key decision points and implementation points for commands.

Specific examples of structure-based abstractions and their influences on controller situation awareness and decision-making processes are discussed in Chapter 6.

5.5.2 Structure's Influence on Controller Techniques and Strategies

Structure can also influence controller cognitive processes through the techniques and strategies used by a controller. In the modified cognitive process model in Figure 5–17, these strategies and techniques reside in long-term memory. Some techniques and strategies take advantage of the presence of structure to transform the task. Others take advantage of structure-based abstractions and the resulting simplifications of the working mental model.

Controllers use strategies and techniques that take advantage of structure to directly simplify and/or transform the controller's task. Controllers can employ strategies of using procedures that allow parts of the task to be offloaded to other controllers or pilots in the air traffic situation. For example, under some circumstances, controllers can modify their task by delegating separation responsibility to pilots. Controllers also described using the structure as part of strategies to expedite aircraft through their airspace. As shown in Figure 5–15 above, giving an aircraft a 'shortcut', by clearing it to a fix downstream of the sector, expedites aircraft through the sector and quickly removes them from the task.

Others strategies and techniques take advantage of structure-based abstractions and the resulting simplifications of the working mental model. Controllers were observed using strategies of enforcing aircraft conformance to the pre-existing structure within the sector by denying requests for 'shortcuts' and requiring strict adherence to interface procedures during coordination with surrounding airspace. This enforcement of the structure allows controllers to rely on simpler working mental models that take advantage of pre-existing structure-based abstractions.

Controllers also use techniques of using specific commands to impose structure directly on the situation, allowing simpler working mental models to be used. The imposed structure acts a basis for simplifying abstractions or as part of additional simplification techniques. For example, controllers have been observed using commands to impose a constant velocity on aircraft in the situation (Davison and Hansman, 2003). The resulting standardization of the dynamics allows a controller to use structure-based abstractions and a simpler working mental model, making it easier to project future states and monitor the situation.

5.5.3 Costs and Challenges of Structure's Influence on Cognitive Processes

Structure's influence on abstractions, strategies and techniques helps reduce cognitive complexity but can also create biases that result in inappropriate decisions. Biases can develop from over-reliance on structure-based abstractions and techniques / strategies based on structure. Structure-based abstractions can contribute towards confirmation bias, or the tendency to interpret incoming information in ways that confirm pre-existing representations of a situation. While structure creates regular patterns, assumptions about future aircraft behavior based on those patterns may not always be appropriate.

Furthermore, the structure constrains aircraft trajectories, introducing inefficiencies and making the system less responsive to user needs. For example, the underlying route structure is rigid and unresponsive to changes in weather conditions such as convective weather or wind.

5.6 Chapter Summary

This chapter described key elements of structure identified in the ATC operating environment. Three distinct types of structure were identified and presented as part of a structure hierarchy: patterns, procedures, and framework layers.

As an important factor in controller strategies to reduce cognitive complexity, structure was explicitly incorporated into the cognitive process model. Using the model, and informed by observations, key influences of structure were identified in the controller cognitive process model.

Key influences on the operating environment include affects on the dynamics of an air traffic situation, the controller's task, and the commands available for modifying the evolution of the air traffic situation. Key influences on controller cognitive processes include structure's role as a basis for abstractions simplifying a controller's working mental model, and its use in strategies and techniques.

Based on the observations, the influence of structure on the abstractions used by controllers to simplify their working mental model is one of the most powerful and important influences of structure. The following chapters provide specific examples of these structure-based abstractions and use part-task experiments to explore more deeply their impact on controller cognitive complexity.

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CHAPTER 6 Structure-Based Abstractions

Structure-based abstractions reflect a controller's internalization of the effects of structure on the operational environment. As simplifications of the controller's working mental model, they are powerful mechanisms for mitigating cognitive complexity. Figure 6–1 highlights, within the modified cognitive process model, the relationship between structure in the operational environment and structure-based abstractions. Based on the observations presented in Chapter 4, multiple types of structure-based abstractions were identified:

- standard flow,
- critical point,
- grouping, and
- responsibility.

This chapter describes each type of abstraction and how it simplifies a controller's working mental model. Examples are presented of the resulting impact on key controller cognitive processes. The second half of the chapter discusses how the use of standard flow abstractions responds to changes in the number of aircraft being controlled.

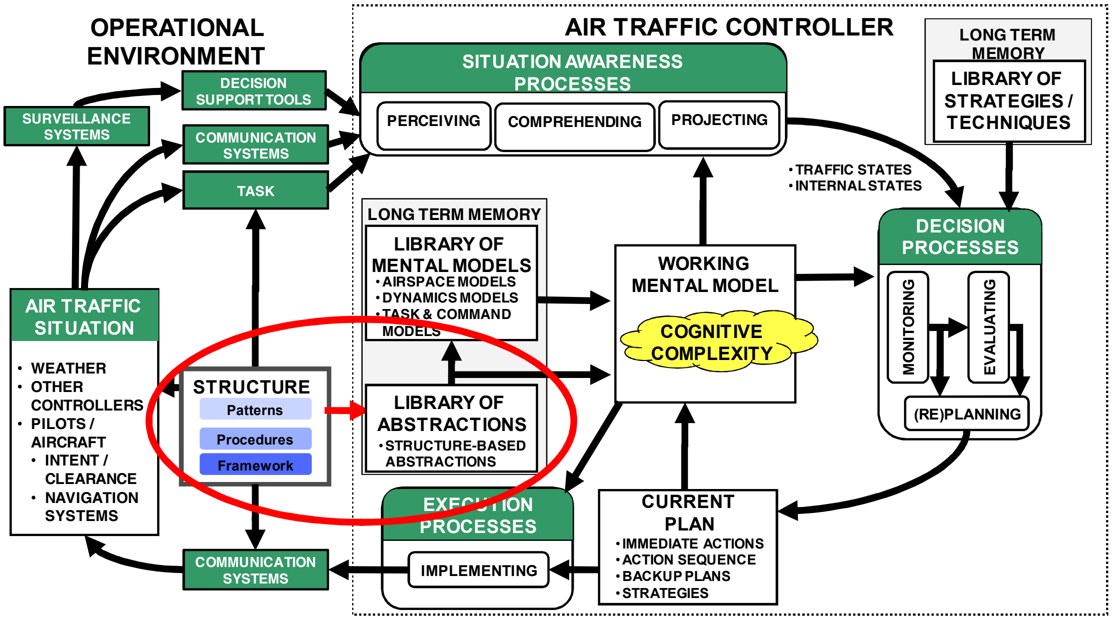

Figure 6–1. Structure-based abstractions in modified cognitive process model.

6.1 Standard Flow Abstractions

Standard flow abstractions are internalizations of the standard flows of aircraft through and near a sector. Standard flows are recurring patterns of aircraft sharing common lateral paths; in a standard flow aircraft are typically 'in-trail' of each other. A standard flow may span multiple altitudes, include vertical behaviours such as climbs or descents, and can merge and/or cross with other flows in the airspace.

Standard flows are typically the product of procedure and framework layer elements such as jet routes and arrival routes (Figure 6–2). Due to their dependence on these static elements, standard flows through a sector tend to be persistent and stable. Analysis of traffic across multiple years and time periods showed the same basic patterns of traffic through a sector persisting. For example, visualizations depicting 24 hours of traffic through the Utica sector in Boston Center spanning a seven-year period, shown in Figure 6–3, illustrate that the dominant structure of a primary east-to-west flow is remarkably stable and persistent across time.

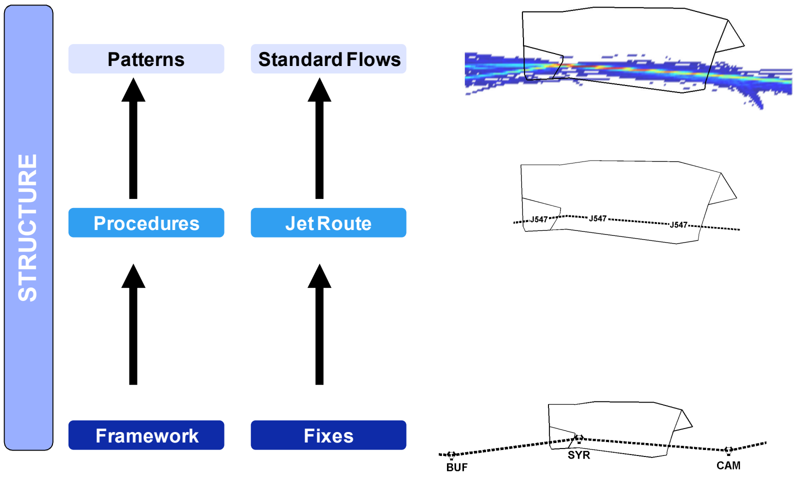

Figure 6–2. Standard flows are examples of pattern layer structure, dependent upon elements in lower layers.

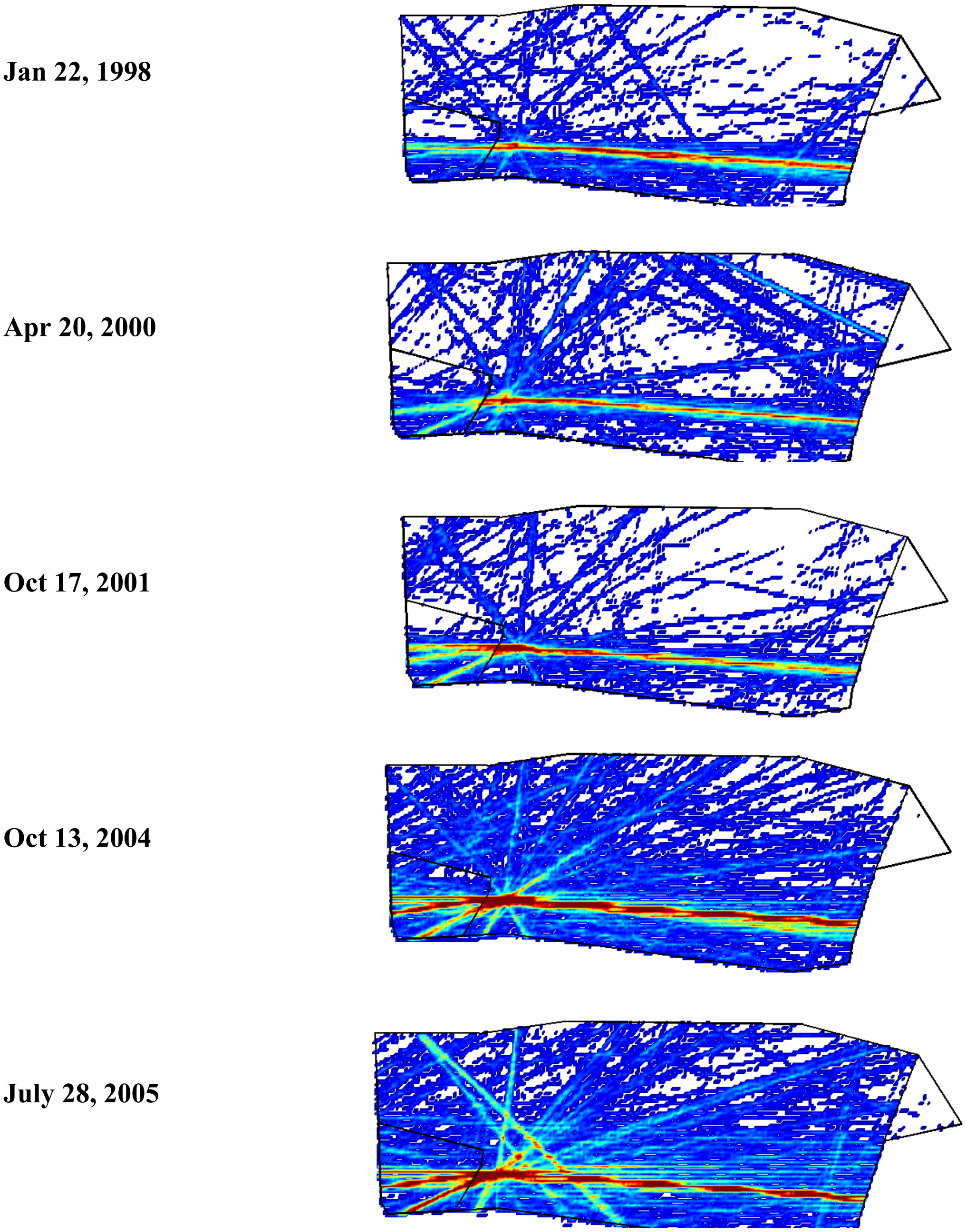

Figure 6–3. 24 hours of traffic through Utica Sector.

The persistent and repeated nature of standard flows provides an important and powerful basis for simplifying abstractions. Standard flow abstractions reflect a controller's generalized expectation of aircraft trajectories in those flows within and near a sector. The abstractions are powerful as they incorporate a wide range of higher-level attributes including aircraft altitudes, typical events and requests from pilots (e.g. top-of-descent points for arriving aircraft), commands commonly given (e.g. to meet a crossing restriction), and known conflict points. These attributes simplify many of the controller's core cognitive processes. Standard flows can be present even if they are infrequently populated with aircraft. For example, standard routings to secondary airports can also support standard flow abstractions.

Standard flow abstractions are important foundations and anchors in a controller's working mental model. When asked to describe an air traffic situation during the site visits, controllers often started with a description of the flows of traffic through the sector. Events, tasks, and individual aircraft were discussed in relation to those flows. Aircraft were often categorized by their membership in the underlying flows and controllers emphasized the importance of understanding how aircraft in the flows within and near a sector impact each other.

There are many mechanisms by which standard flow abstractions simplify the working mental model. A key simplification mechanism is reducing the "order," or degrees-of-freedom, of the controller's working mental model (Section 5.5.1). By creating common trajectories and standardizing the relative dynamics of aircraft, standard flows reduce the number of unique degrees-of-freedom required to project the air traffic situation (Figure 6–4).

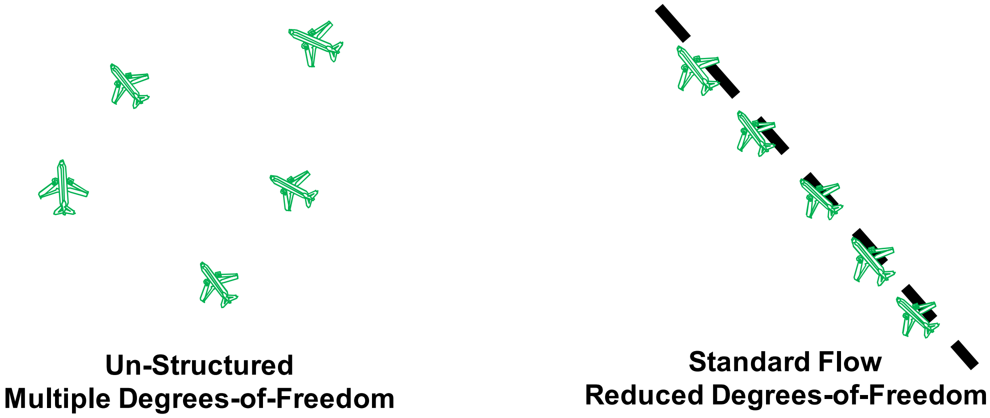

Figure 6–4. Standard flow abstractions help reduce degrees-of-freedom and hence "order" of an air traffic situation.

Standard flow abstractions also simplify the working mental model by allowing standardized dynamics to be used in place of individual dynamics for aircraft on the standard flow. Standard flow aircraft follow common paths, have similar exposure to disturbances such as wind, and create similar tasks (e.g. conflicts, procedure requirements). As a consequence, controllers can use standardized representations of the dynamics of aircraft in the flow, simplifying the working mental model.

6.1.1 Operation of Standard Flow Abstractions

This section presents examples of how use of standard flow abstractions helps controllers manage their task, simplify the maintenance of situation awareness, and perform key decision processes leading to the development of a current plan.

Decomposing the Task. Standard flow abstractions help controllers manage and regulate the task by decomposing the task into multiple, simpler parts. Standard flow abstractions classify aircraft as standard or non-standard based on their relationship to the standard flows in a sector. Decomposing the task into standard and non-standard aircraft allows a controller to use smaller, simpler working mental models customized to the specific task. For example, standard flow abstractions can be used to decompose the traffic in Figure 6–5 into several simpler problem spaces: the aircraft within each of the two merging flows, the aircraft in the merged flow, and the non-standard, or remaining aircraft.

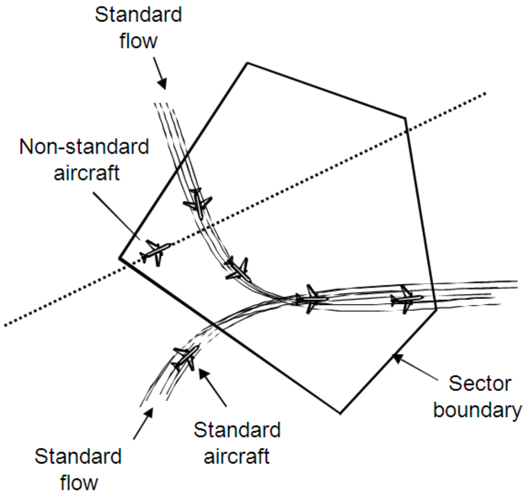

Figure 6–5. Standard flow abstractions decompose situation into standard and non-standard aircraft.

Projecting. The importance of standard flow abstractions for projection was clearly expressed by one controller: "standard routings makes projection infinitely easier."[21] One of the most important mechanisms by which standard flow abstractions simplify projecting is by supporting recognition of future states and locations of aircraft, rather than deliberate calculation during the projection process.

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[21] October 20, 2001, Cleveland Center, Air Traffic Controller.

Controller responses during the focused interviews and field observations showed that knowledge of the standard flows provides immediate access to future aircraft positions. Across multiple facilities and visits, controllers reported that seeing an aircraft at a particular position and heading gives a controller instantaneous access to the aircraft's future position. As one interview participant stated, "Experience allows [a] controller to look at [an] aircraft and already know where [its] going to be."[22]

Standard flow abstractions also make projections more accurate. Aircraft routes often have turns or other changes to the trajectory that make straight-line extrapolation of future aircraft positions inappropriate. Failing to account for flight planned turns can lead to losses of separation when aircraft turn "unexpectedly" (Transportation Safety Board, 2001). By incorporating the known turns and other dynamics associated with the underlying reference elements such as jet routes, standard flow abstractions standardize the dynamics used in the projections, making it easier to create more accurate projections (see Figure 6–6).

Standard flow abstractions also incorporate typical commands used for aircraft in the flow. Typical commands include short-cuts, climbs and descents, or speed assignments. Analysis of the commands given to aircraft exiting Sector D (Figure 4–14) into a Boston TRACON sector (Figure 5–14) showed that 83% of the aircraft were commanded to cross the BRONC intersection at 11,000 feet. This is consistent with the expected altitude based on the procedure shown in Figure 5–14. Incorporating typical recurring commands into the working mental model simplifies projection by standardizing the future changes to an aircraft's trajectory.

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[22] October 19, 2001, Cleveland Center, Traffic Management Unit personnel.

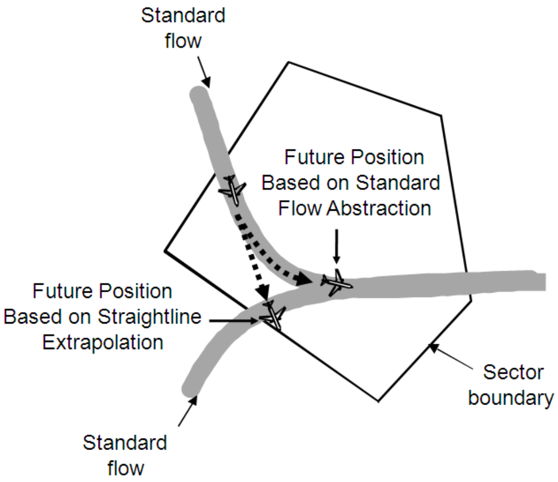

Figure 6–6. **Standard flow abstractions simplify and make more accurate projections of future aircraft positions.**

Monitoring. Standard flow abstractions simplify the monitoring process by providing a clear basis for determining whether an aircraft is conforming to its clearance. During the focused interviews, controllers described knowledge of the standard flows in a sector as useful for getting a "sense of something wrong with the picture."[23] Aircraft in positions that are inconsistent with the standard flow abstractions quickly stand out. For example, Figure 6–7 illustrates how standard flows can make an aircraft missing a turn quickly stand out as a non-conforming aircraft.

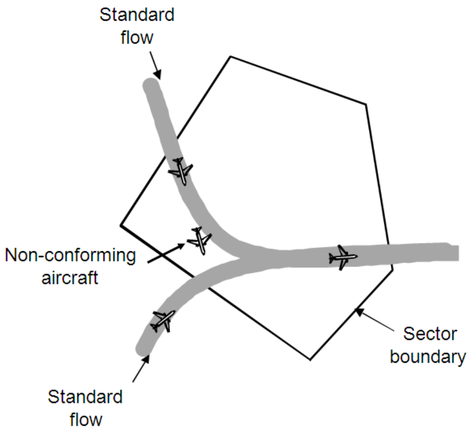

Figure 6–7. **Standard flow abstractions support monitoring for non-conformance with expected aircraft trajectories.**

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[23] October 2001, Cleveland Center, Traffic Management Unit personnel.

Evaluating. Standard flow abstractions simplify evaluation of the air traffic situation by suppressing unnecessary comparisons. A controller's standard flow abstractions incorporate knowledge of how aircraft in the standard flow relate to other structural elements such as other standard flows or airspace boundaries (e.g. Special Use Airspace). In cases where the standard flow structure eliminates the possibility of a conflict, evaluation of the relationship is unnecessary. For example, knowing that arriving and departing flows are laterally separated by a procedure can allow a controller to ignore comparisons between aircraft in those flows.

Evaluating is also simplified by standard flow abstractions reducing the order of the working mental model. Standard flow abstractions reduce order by eliminating relationships in the working mental model that are irrelevant due to the consequences of the in-trail arrangement of aircraft in the flow. The relative positions of aircraft within the flow preclude certain conflicts from occurring; consequently only nearest neighbor interactions need to be evaluated.[24] Figure 6–8 shows three aircraft in trail on a standard flow. If the lead two aircraft (A and B) are safely separated, and the trailing two aircraft (B and C) are separated, a standard flow abstraction will reflect the lack of a need for comparisons between the first and last aircraft (A and C) as they will also generally be separated.

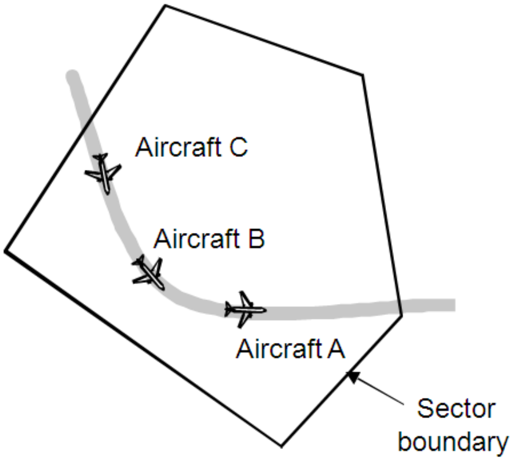

Figure 6–8. Standard flow abstractions reduce need for comparisons between in-trail aircraft.

(Re)Planning. Standard flow abstractions simplify the planning process by providing known, pre-evaluated commands for aircraft in the standard flow that can be quickly integrated into the

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[24] Technically, the arrangement prevents certain conflicts from occurring earlier than other conflicts. For example, in Figure 6–8 aircraft C could conflict with aircraft A, but this would occur at a later time than it would conflict with aircraft B.

Current Plan. Standard flow abstractions associate typical commands with aircraft trajectories, reducing the amount of planning effort required for aircraft in the standard flow. Typical commands associated with a standard flow might include turns providing standard short-cuts, a common airspeed assigned to all aircraft, or altitude changes to begin a descent to an airport.

Standard flow abstractions also simplify planning through quicker identification of feasible command options and of airspace available for aircraft maneuvering. Knowledge of standard flows in the airspace was described as capturing “particular constraints on what actions can do.” Limits on the magnitude of commands, such as the sharpness of a heading change, were associated with particular flows of aircraft. For example, “never turn [Boston traffic] more than 20 degrees” as a sharper turn “will put [the Boston traffic] into someone else.”[25] This helps controllers determine what control commands are feasible. In addition, knowing how the standard flows in a sector relate to other static elements such as holding patterns was reported to make a “big difference in evaluating what [it] takes to miss that holding pattern.”[26]

6.1.2 Summary

In summary, there are multiple ways by which standard flow abstractions simplify the working mental model used in various cognitive processes. Decomposition of the situation simplifies task management and allows situations to be broken down into simpler, easier problems. Standard flow abstractions filter out ‘pre-solved’ relationships between aircraft, based on the independence introduced by the arrangement of aircraft into the flow, making the evaluation and projection processes easier. Finally, standard flow abstractions incorporate typical commands, making identification of feasible commands and airspace available for maneuvering quicker and easier.

6.2 Critical Point Abstractions

A third example of a type of structure-based abstraction are critical point abstractions. Critical point abstractions are generalizations of high priority regions of a sector. Typically, these high priority regions, or critical points, are locations where controllers know to expect potential conflicts or other sources of recurring problems (e.g. overshooting a turn in an airway). During the site visits, a variety of terms were used to describe these points: “confliction points”, “hot-

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[25] October 2001, Cleveland Center, Traffic Management Unit personnel.

[26] October 20, 2001, Cleveland Center, Air Traffic Controller.

spots", "convergence points" and "flash points." All of the terms appear to describe a common concept of critical points.

Pattern layer elements of structure such as merge points, crossing points, and bends in standard flows can act as the direct basis for a critical point abstraction. Several examples of critical points in the form of merge points in the standard flows in traffic destined Chicago's O'Hare airport (ORD) can be seen in Figure 6–9. Critical points are often the consequence of procedure and framework layer elements of structure such as airways, jet routes, and arrival routes. Those elements concentrate aircraft trajectories over common locations, producing consistent and predictable locations of conflicts and other critical events and therefore a basis for a critical point abstraction.

During the site visits and in the literature controllers described the lack of known critical points as an important complexity factor. One controller stated that adding one aircraft "with strange [and] different confliction points is more difficult. Throwing in more than one like that compounds the problem."[27] Aircraft that are on direct or random routings do not have the same degree of predictability as to where conflicts will occur. Brown (2004c) described this as "conflicting random routes are much more difficult to "see" in your mind's "eye" than two aircraft on airways."

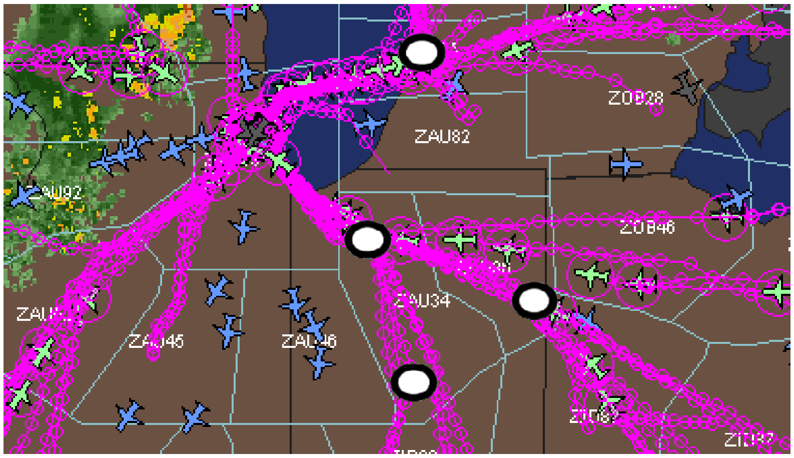

Figure 6–9. Examples of critical points in the form of merge points in traffic destined Chicago.

Similar to standard flows, critical point abstractions reduce the order of the working mental model. Critical point abstractions allow controllers to transform problems from multi-

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[27] October 2001, Cleveland Center, Air Traffic Controller.

dimensional spaces to simpler one-dimensional spaces focused on behavior at or near the critical point. Transforming problems in this way allows controllers to further decompose their task and treat aircraft independently. Having established that projected arrival times at the critical point are compatible with their current task (e.g. separation requirements, traffic management initiatives etc…), each aircraft's progress towards the common point can be monitored independently.

Critical point abstractions also help controllers organize their working mental model and prioritize their tasks. By capturing the patterns in the locations of critical events, critical point abstractions help focus a controller's working mental model on the finite number of critical locations.

6.2.1 Operation of Critical Point Abstraction

This section presents examples of how use of critical point abstractions reduce cognitive complexity and make it easier to perform the cognitive processes captured in the modified cognitive process model in Figure 6–1.

Perceiving. Critical point abstractions focus controller attention on the most relevant and important parts of the air traffic situation. As such, critical point abstractions simplify perceiving by focusing a controller's scan on those areas of the sector where problems are most likely to occur.

Projecting. Critical point abstractions are powerful simplifications for controller projection processes. In the field observations, controllers described using the critical points as projection points; they would anticipate the time and relative arrangement of aircraft at the future time corresponding to when the aircraft were expected to reach the critical point. By using critical point abstractions, controllers transform multi-aircraft, multi-timestep projections over the large space of their sector into a projection of the time-of-arrival at the fixed location of the critical point. The resulting one dimensional problem is significantly simpler and easier to project.

Monitoring. Critical point abstractions simplify monitoring by focusing controller attention on high priority areas of the sector. More frequent monitoring is often required at critical points due to limited time to respond, and/or the relationship of aircraft trajectories with other structural elements such as airspace boundaries or other flows. Critical point abstractions reflect these considerations, as well as the consequences should an aircraft deviate from its clearance, allowing a controller to adapt the frequency of monitoring and their tolerance for deviations.

Figure 6–10 shows an example of a critical point observed during field observations conducted at Boston Center. In the sector, aircraft on the standard flow to the Newark (EWR) airport were observed making the right turn shown in the figure. The location of the turn was reported to be a key critical point for the sector. Controllers reported that wind, inattention, or other factors may cause an aircraft to miss the turn and/or begin the turn late. A late turn could, and was observed to, make an aircraft encroach on the boundary with the neighboring sector. Controllers reported that this consequence forced them to pay particular attention to aircraft near this area of the situation display.

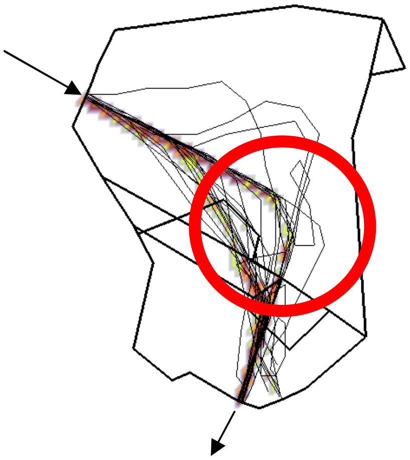

Figure 6–10. Critical point due to aircraft trajectory changes.

Evaluating and Planning. Critical point abstractions significantly simplify the process of evaluating a situation and resolving problems that are detected within it. Because of the close parallels between evaluating and planning, the ways in which critical point abstractions simplify one are also applicable to the other.

Critical point abstractions simplify the evaluating/planning process by reducing the search space over which aircraft trajectories are evaluated. Rather than attempting to evaluate all possible future states of the situation, controllers can use critical point abstractions to focus their evaluation on a limited subset of locations in the sector. As illustrated in Figure 6–11, evaluation and planning is simplified as controllers can focus on comparing projected time-of-arrivals at the critical points. This transforms the problem into a simpler one of evaluating one-dimension phasing problems, based on the time-of-arrival at the common point. The use of critical point abstractions to ensure no aircraft are expected to be at the critical point location at the same time also allows the controller to evaluate the situation once. Subsequently, the controller need only monitor that no significant changes affect aircraft times-of-arrival.

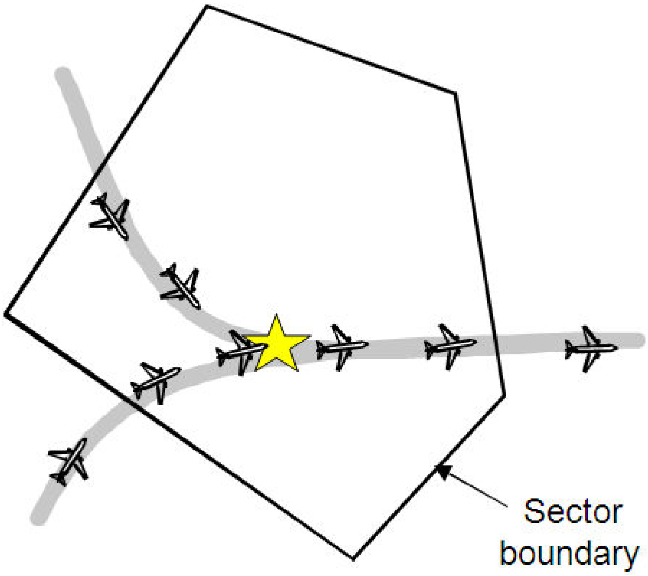

Figure 6–11. Critical point (star) supports evaluation and planning at a reduced number of points.

6.2.2 Summary

Critical point abstractions transform multi-aircraft, multi-time step projections into a simpler projection of the time-of-arrival at the fixed location of the critical point. Evaluation and planning is simplified as the critical point abstractions allow the controller to consider one dimensional, time-of-arrival, phasing problems. Critical point abstractions also support more focused monitoring and perceiving processes.

6.3 Grouping Abstractions

Grouping abstractions are a second type of structure-based abstraction. A grouping abstraction collects together parts of a situation, typically aircraft, within the working mental model. While primarily used for aircraft, grouping abstractions can also include sets of weather objects, such as thunderstorms or airspace such as a group of areas of restricted airspace. Structure forms an important and powerful basis for some of these groups.

There are several structural elements which support grouping abstractions. Patterns in aircraft trajectories, such as flying at distinct and separated flight levels, support abstraction of an air traffic situation into groups based on the independent flight levels. Airways and jet routes consolidate aircraft trajectories, bring aircraft into close proximity; a cluster of aircraft following the same standard flow forms a natural basis for a group. This is distinct from the standard flow abstraction in that the standard flow abstraction reflects common spatial trajectories, whilst the grouping abstraction is capturing the relative proximity of a set of actual aircraft. Such abstractions capture temporal consequences of structure; controllers frequently described situations with respect to the "push" or "bank," a concentration of aircraft to a single arrival airport over a short period of time.

Generalizations of aircraft performance also provide bases for a subset of grouping abstractions, identified as performance abstractions. Performance abstractions are a controller's generalizations of the effects of aircraft properties and pilot behavior on aspects of an aircraft's dynamics. These include climb/descent rates, speeds, navigation capabilities, and/or willingness to penetrate turbulence. There are many sources of commonalities in performance, ranging from the operating culture or standard operating procedures specific to an airline or airport, to the impacts of time-of-day, climate and temperature (e.g. "[during the summer] North Atlantic departures are heavy and will climb slow"), to the underlying dynamics of aircraft themselves. For example, excess power available on some aircraft can make a large difference in their climb capabilities.

The structure forming the basis for a grouping abstraction appears to have at least one or more of three important effects. The basis can introduce constraints such that the dynamics of members of the group can be considered independent of events occurring outside the group. This reduces the "order," of the working mental model by suppressing degrees-of-freedom and irrelevant relationships from the working mental model.

A second effect is to be a source of common dynamics of the set of objects in a group; this minimizes differences in the dynamics of objects in the group, preserving their relative positions. This makes abstraction of the elements in the group into a singular object in the working mental model effective and appropriate.

A third effect is related to performance-based grouping abstractions. Structure can be the source of consistent dynamics amongst multiple aircraft considered to be a group but which are not spatially related. This makes it appropriate and effective to substitute the dynamics of the broader group for each individual aircraft's detailed and aircraft-specific dynamics.

6.3.1 Operation of Grouping Abstractions

This section presents examples of how use of grouping abstractions helps controllers manage their task, simplify the maintenance of situation awareness, and perform key decision processes leading to the development of a current plan.

Decomposing the Task. By capturing structure's effect of segregating parts of a situation, grouping abstractions are powerful means of supporting decomposition of the task. Similar to the standard flow abstractions, grouping abstractions allow the controller to break the task up into smaller, simpler parts based on non- or minimally- interacting groups.

Figure 6–12 shows a simple illustration of how a controller might abstract the situation on the left into the three groups shown on the right based on independent flight levels. This allows a controller to decompose their task into multiple sub-problems, one for each altitude; projection, evaluation and planning can each be performed for each altitude level independently and with working mental models appropriate for each sub-problem. There are limits to this use; the appropriateness of such a decomposition relies on there being few cases of aircraft changing altitudes and therefore compromising the presumed independence between groups.

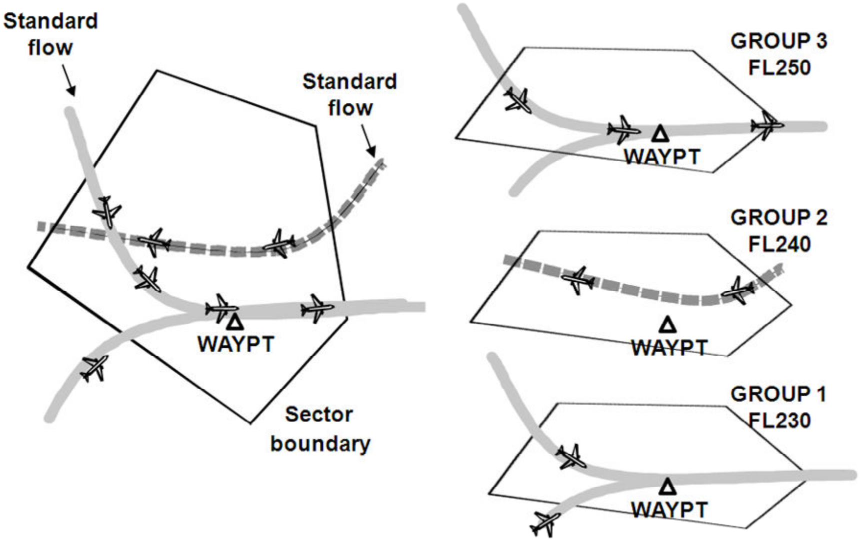

Figure 6–12. Grouping abstractions can be based on distinct, independent, flight levels.

Projecting. There are several different ways by which grouping abstractions simplify projection. Grouping abstractions suppress the details of the relative motion between aircraft within the group. This allows a controller to project the motion of the group only, reducing the number of items projected and thus making projection easier. Such groups are often based on spatial proximity and temporal clustering of aircraft. For example, in Figure 6–13, the motion of the group of four aircraft being merged together can be projected forward based on the average speed of aircraft in the group, and independent of the details of how the aircraft are merged.

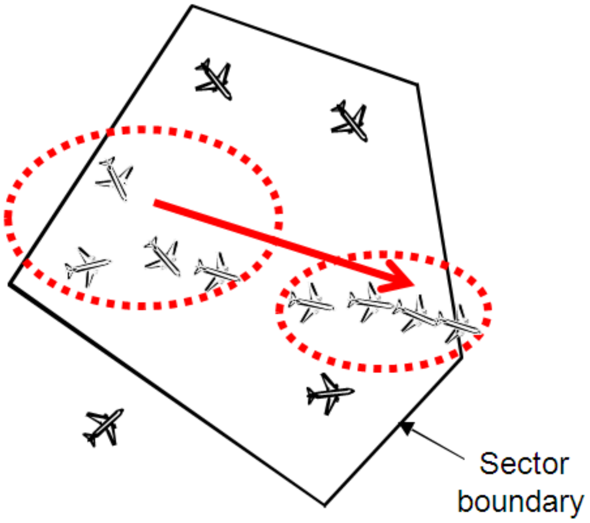

Figure 6–13. **Aircraft abstracted into a group simplify projection.**

Performance based grouping abstractions simplify projection by providing standardized dynamics for individual aircraft that are associated with a group. Such abstractions replace specialized detailed dynamics specific to an individual aircraft in the situation. A simple example of such a grouping abstraction would be ‘all regional jets climb slow at altitude’; this abstraction is used in place of considering the exact performance of the particular type of regional jet. Such an abstraction simplifies the working mental model, allowing quicker and less cognitively demanding, but still effective, projection of future altitudes of the jet.

Evaluating. Grouping abstractions also influence how controllers evaluate a situation. An important part of evaluating is comparing current and projected states against the separation standards, procedural requirements, pilot requests, and other drivers of the controller’s task. Grouping abstractions help simplify this evaluation by incorporating known consequences of the structural basis on the relationships between aircraft. Rather than individually evaluating each pair of aircraft in the situation, grouping abstractions break the situation down into a smaller number of discrete parts, reducing the order of the working mental model.

The potential of grouping abstractions to reduce the order of a working mental model is suggested by considering the number of pair-wise relationships amongst a set of objects, such as the aircraft in a sector.[28] Evaluating the potential for conflicts amongst N aircraft requires a working mental

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[28] The number of pair-wise comparisons is used as an illustrative example but is not meant as an absolute definition of complexity.

model capturing the ½N(N-1) pair-wise relationships between the aircraft. Using a grouping abstraction to split the aircraft into two groups, and considering each group independently, reduces the number of relationships in the working mental model to ~⅛N(N-2) for each group.[29] Figure 6–14 shows the greater than 75% reduction in the number of relationships that results.

More generally, grouping abstractions, such as those representing the discrete altitude levels shown in Figure 6–12, can break the situation into several independent groups. As the number of aircraft increases, parsing the situation into multiple independent groups becomes increasingly powerful. If the N aircraft are divided into *m* groups, Equation 6–1 shows the number of relationships per group required in the working mental model.

$$\#\text{ of relationships/group} = \frac{1}{2}\frac{N}{m}\left(\frac{N}{m}-1\right)$$

Equation 6–1

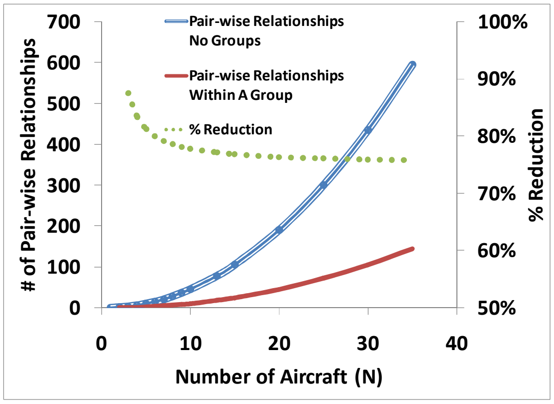

Figure 6–14. **Reduction in number of pair-wise relationships by parsing N aircraft into two groups.**

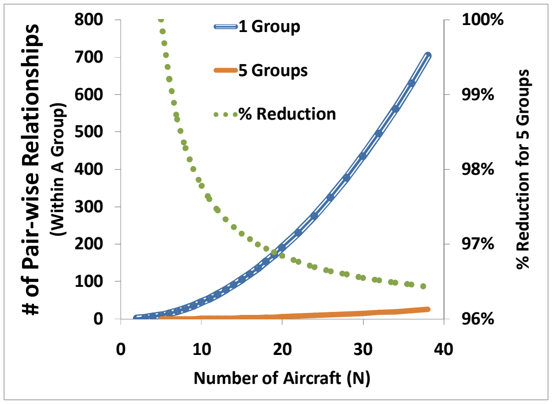

Figure 6–15. **Number of pair-wise comparisons in each group for a set of aircraft divided into 5 groups.**

The reduction in the number of relationships required in the working mental model scales with the inverse of the square of the number of groups, or $(1-1/m^2)$%, for large values of N. This potential power to reduce the order of the working mental model is illustrated for the case of m=5 groups in Figure 6–15.

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[29] This analysis ignores the physical impossibility of having ½ an aircraft in each group when N is odd.

While powerful at simplifying the working mental model, decomposing the situation into 5 groups in Figure 6–15 requires consideration of 5 discrete, though simpler, problems. Maximal use of decomposition, for example dividing N aircraft into *m*=N groups, is an extreme case; while each group would be as simplistic as possible, the total cognitive effort to manage the distinct groups and process each group would overwhelm those benefits.

Similar analysis shows the potential power of using grouping abstractions to abstract the problem into the relationships between the *m* groups themselves. If the relationships between aircraft within the group can be ignored, only ½*m* (*m*-1) pair-wise relationships between the aircraft are required. The most powerful case is *m*=2, where grouping abstractions reduce the working mental model to only the relationship between the two groups which is significantly easier to evaluate.

Planning. Grouping abstractions simplify planning by allowing a controller to develop a plan for the group, rather than multiple plans for individual aircraft. The plan developed for one aircraft can be extrapolated quickly and easily to all aircraft in the group. Figure 6–16 illustrates a simple example of this mechanism where a controller can develop a plan based on deviating a group of aircraft around the same side of a thunderstorm.

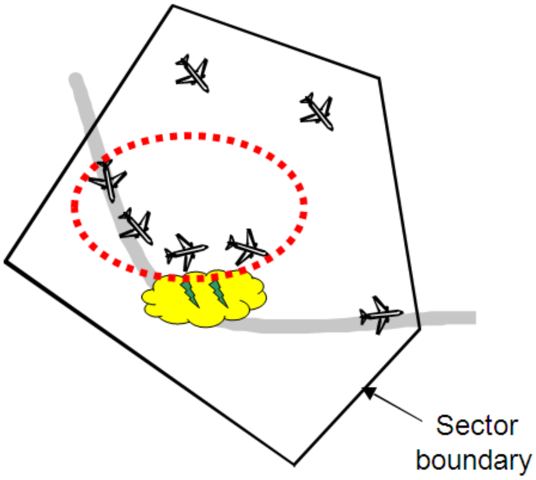

Figure 6–16. Grouping abstractions simplify planning of a group around disturbances such as thunderstorms.

Performance abstractions incorporate the capabilities of aircraft in the group to perform certain maneuvers, or accept particular commands. This simplifies planning by reducing the range of potential actions that are considered. For example, aircraft navigation capabilities determine the types of commands a controller can give an aircraft. Aircraft equipped with Area Navigation (RNAV) navigation systems can navigate to a wider range of waypoints than those equipped only with VOR-based navigation systems. Grouping abstractions capturing these differences allow a controller to quickly filter the set of potential commands that could be given to an aircraft.

6.3.2 Summary

In summary, there are multiple ways by which grouping abstractions simplify the working mental model and help controllers perform key cognitive processes. Decomposition of the situation simplifies task management and allows situations to be broken down into simpler, easier, problems. Grouping abstractions support simpler projection by aggregating parts of a situation into single objects that have simpler dynamics. Projection is also simplified by standardizing the dynamics based on membership in a group with common performance characteristics. Grouping abstractions also reduce the number of pair-wise comparisons made in evaluating a situation. Finally, grouping abstractions simplify planning processes by supporting the extrapolation of resolution actions to all members of a group and by simplifying the process of identifying feasible commands for aircraft within a group.

6.4 Responsibility Abstractions

Responsibility abstractions are a final example of a type of structure-based abstraction. Responsibility abstractions internalize structure's effect on the task and the delegation of portions of the task to other agents or parts of the system.

Responsibility abstractions are based on elements of structure at the framework and procedure layers of the structure hierarchy. Airspace boundaries, illustrated in Figure 6–17 eliminating aircraft from the task, are a simple example of a basis of a responsibility abstraction. The observation of controller use of an Area of Regard (see Section 4.4) suggests that responsibility abstractions based on boundaries are flexible and adaptive. While the underlying structure may delimit formal regions of jurisdiction and responsibility, practical considerations dictate that the decomposition of tasks between sectors can be complicated.

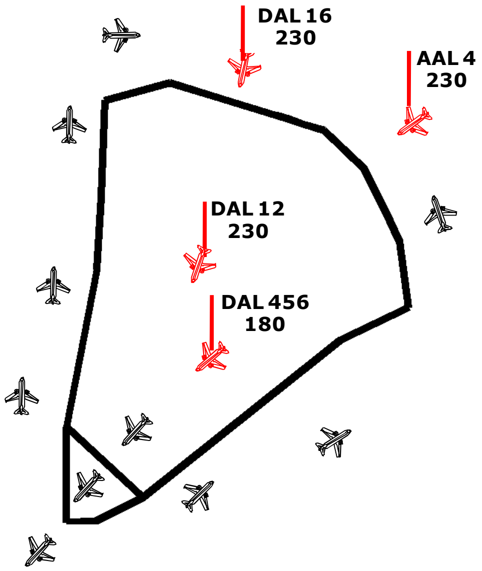

Figure 6–17. Responsibility abstractions limit scope of monitoring, evaluating and projecting processes.

Other bases of responsibility abstractions include procedures that allow controllers to offload parts of their task to pilots. Under certain conditions, pilots can be instructed to “maintain visual separation with the traffic.” This delegates the separation assurance task from the controller to the pilots. Procedures are also in place that allow a controller to delegate the timing of trajectory changes to pilots. For example, pilots can be instructed to “descend at pilot’s discretion” or be cleared direct to a way point “when able.” Controllers can capture the effect giving such an instruction has on the responsibility of managing each aircraft’s trajectory through a responsibility abstraction.

Responsibility abstractions incorporate controller knowledge of how tasks are distributed along and near airspace boundaries. Interface procedures can transfer responsibility for certain actions, for example clearing an aircraft to a fix, to downstream sectors (Figure 5–5). Controllers approving a point-out (Section 3.3) will have aircraft passing through their sector; responsibility abstractions capture controller expectations that the controller requesting the point-out is retaining responsibility for performing the separation responsibility task for that aircraft.

6.4.1 Operation of Responsibility Abstraction

Responsibility abstractions help simplify the maintenance of situation awareness, and key decision processes leading to the development of the controller’s current plan.

Task Delegation. As described above, responsibility abstractions capture in the working mental model the removal of parts of a controller’s task through delegation to other agents (e.g. pilots, controllers) in the situation. This allows controllers to eliminate certain tasks, such as tracking the relative positions of two aircraft that have been delegated visual separation responsibility.

Perceiving and Projecting. Responsibility abstractions based on airspace boundaries provide limits on the events and objects in the situation that are relevant to a controller’s situation awareness. As such, they provide natural filters on the spatial and temporal horizons of the perceiving, and projecting processes. Responsibility abstractions capturing the effects of separation delegation simplify the projection of future states as there is one less relationship between aircraft that must be tracked in any projections of future states. However, delegating can have a secondary effect that conversely increases the difficulty of projecting. Delegating adds uncertainty into the dynamics of the individual aircraft as the controller does not know what maneuvers the pilots will use to maintain visual separation.

Evaluating and Planning Responsibility abstractions provide filters that allow a controller to limit the number of problems and which problems are considered in the evaluating and planning processes. Delegating responsibility to pilots offloads some of the requirements that would otherwise need to be checked as part of the evaluation process.

6.5 Summary of Abstraction Mechanisms

Several of the mechanisms by which structure-based abstractions simplify mental models are common across the four types of structure-based abstractions presented above. Mechanisms common across more than one type of abstraction include:

- ***Minimizing the order or degrees-of-freedom:*** Standard flow, grouping and critical point abstractions reduce the number of dimensions required to capture the dynamics of the situation, simplifying the working mental model.
- ***Task decomposition:*** standard flow, and grouping abstractions support decomposition of the task into smaller, simpler, parts.
- ***Reducing comparisons:*** standard flow, grouping, and responsibility abstractions eliminate the need to evaluate relationships between independent parts of the situation, simplifying evaluation and planning.
- ***Command recognition:*** standard flow and grouping abstractions simplify planning by capturing pre-evaluated resolution actions and quick recognition of appropriate and feasible commands.

Other mechanisms are specific to individual abstraction types. Critical point abstractions have powerful roles transforming working mental models of situations from multi-dimensional to simpler one-dimensional time-of-arrival. Grouping abstractions support use of standardized dynamics, requiring less detailed and aircraft specific projections.

6.6 Dynamic Use of Structure-based Abstractions

Based on observations made during the site visits and a review of the literature, the use of the structure-based abstractions described above is fluid, flexible, and responsive to the current situation. Through their strategies and techniques, controllers are able to manipulate the operational environment and change the dynamics of the air traffic situation as well as the presence of structure, such as standard flows. The cognitive process model recognizes that controller decision-making processes operate in a continuum ranging from the tactical to the strategic. Figure 6–18 shows the modified cognitive process model highlighting these internal states passing from situation awareness to the controller's decision processes.

There are multiple opportunities for controllers to manipulate the operational environment including regulating the rate of incoming aircraft, placing restrictions on the trajectories of aircraft entering the sector, and/or modifying their tolerance for aircraft not conforming to standard procedures and expectations. Controllers can also shed certain parts of the task, for example through not providing or discontinuing flight following services. Sperandio (1978) reported similar observations as have other researchers (Hopkin, 1995; Bisseret, 1981). The ability to modify the operational environment through their commands and actions provides a powerful mechanism by which controllers can manipulate the presence of structure supporting their abstractions.

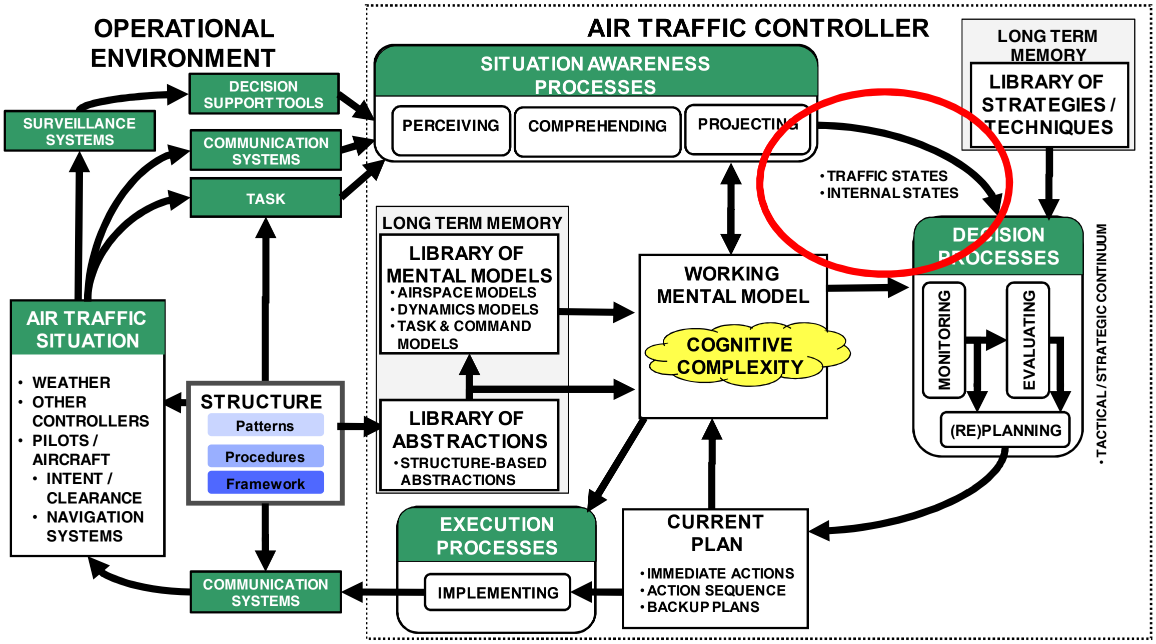

Figure 6–18. **Situation awareness provides awareness of internal states to decision processes.**

A broad analysis of traffic data reported by Howell *et al.* (2003) showed evidence of dynamic shifts in the use of the underlying route structure in response to changes in traffic volume. Howell *et al.* (2003) analyzed the relationship between traffic levels and routing inefficiency in the enroute environment. Inefficiency was measured by computing the excess distance each aircraft flew through a Center. The excess distance was determined by comparing an aircraft's lateral trajectory from point of entry to point of exit with the great circle distance connecting the two points. In order to make comparisons amongst Centers, traffic volume was normalized to the peak volume experienced in each Center.

The data reported by Howell *et al.* (2003), reproduced in Figure 6–19, suggests that there are broad differences in the use of the underlying route structure supporting critical point and standard flow abstractions. At low traffic levels the average excess distance flown grows linearly with the traffic level. When traffic is between approximately 30% and 70% of the maximum center traffic the average inefficiency is approximately constant, consistent with the majority of traffic following the established route structure. Above 70% of the maximum center traffic there is a slight rise in the average excess distance.

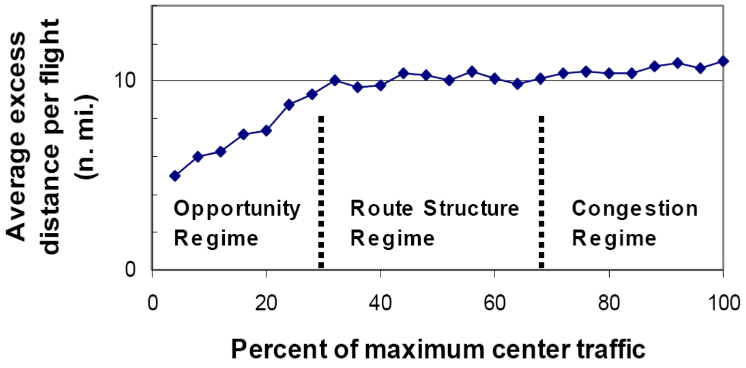

Figure 6–19. **Inefficiency as a function of traffic volume across multiple ARTCCs (From Howell *et al.*, 2003).**

6.7 Operating Modes

The variation in use of standard flows suggests that air traffic controllers operate in distinct operating modes, reflecting the use of different strategies and abstractions in response to the cognitive demands of the air traffic situation. Similar to Sperandio (1978), the modes reflect broad changes in a controller's strategies and practices in response to changes in their task. The use of different operating modes manifests itself in changes in controller actions and can be indirectly observed in the resulting aircraft trajectories. Based on a consideration of previous observations and the data analyzed by Howell *et al.* (2003), four notional operating modes, shown in Figure 6–20, have been identified.

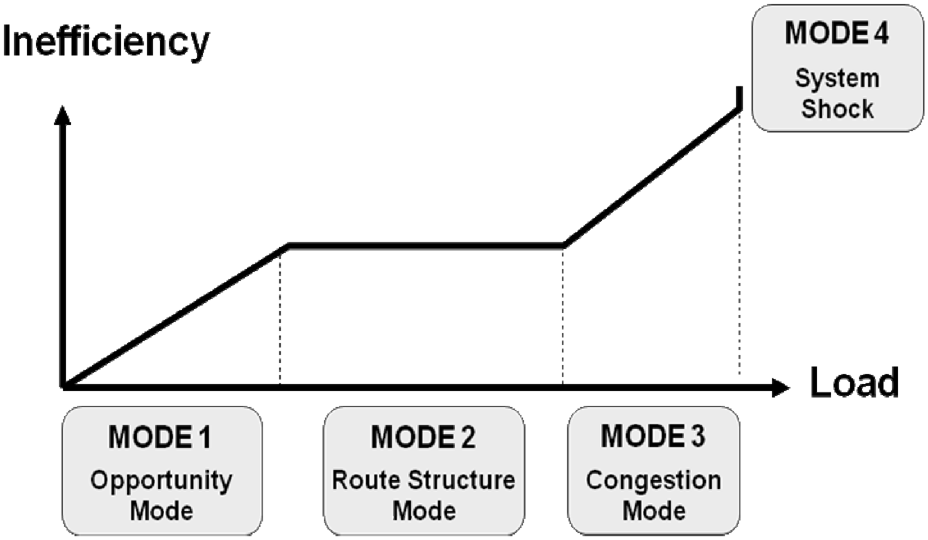

Figure 6–20. Notional air traffic controller operating modes.

6.7.1 Mode 1 – Opportunity Mode

In the opportunity mode, sufficient free cognitive resources exist for the controller to maintain each aircraft individually within the working mental model and seek out opportunities to improve or optimize the aircraft's trajectory. At low traffic levels, the coupling, or degree to which the trajectories of surrounding aircraft are relevant to the evaluating, monitoring, and planning of an aircraft, is typically small. This allows controllers to use pair-wise comparisons effectively without overwhelming the controller's cognitive capabilities. As illustrated in Figure 6–21, in the opportunity mode controllers easily tolerate deviations from standard routings and are able to proactively offer "directs" or shortcuts that lead to more efficient trajectories.

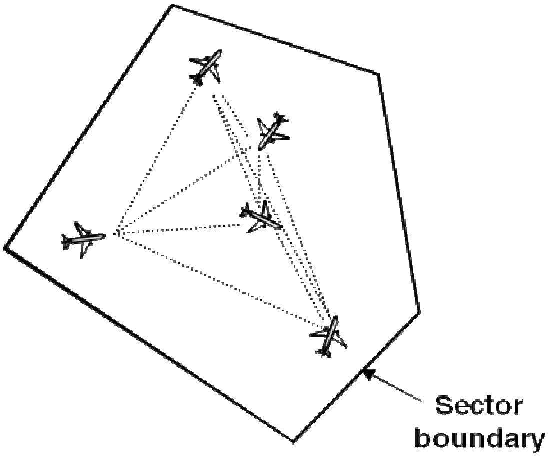

Figure 6–21. Opportunity mode.

6.7.2 *Mode 2 – Route Structure Mode*

As traffic levels increase, controllers appear to rely increasingly on the presence of the standard route structure, as indicated by the plateau in the inefficiency vs. load curve in Figure 6–20. As shown in Figure 6–22, in the route structure mode, most aircraft remain on the pre-determined route structure, leading to an approximately constant average inefficiency per aircraft, even as more aircraft are added to the air traffic situation.

The reliance on the pre-determined route structure allows controllers to take advantage of their structure-based abstractions. The cognitive resources that are freed allow the controller to focus on managing the interactions between aircraft that are 'unstructured' and those that are on structured routes. This allows the controller to control much higher traffic levels than would be possible using the opportunity mode.

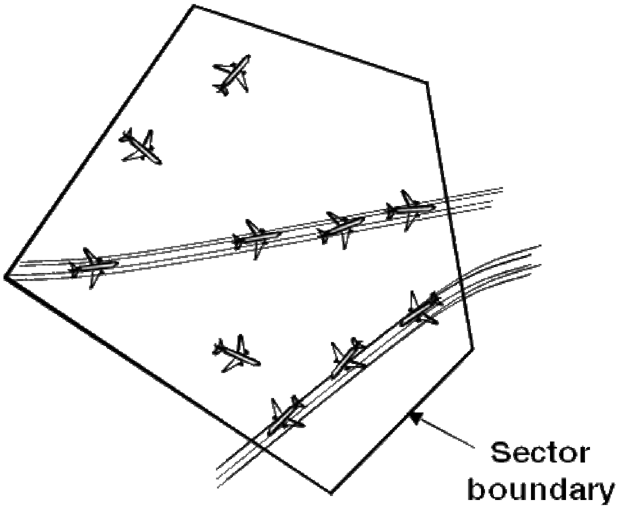

Figure 6–22. Route structure operating mode.

6.7.3 *Mode 3 – Congestion Mode*

As the number of aircraft being controlled continues to increase, flows and merge points can approach capacity limits. It appears that this can trigger use of a congestion mode (Figure 6–23). In the Congestion mode, the interactions between aircraft within the flow become increasingly dominant, undermining the ability of controllers to take advantage of the presence of the standard flows to simplify their mental model of the situation. Interactions within the flow are not driven solely by separation requirements but can also be caused by broader constraints on intra flow spacing such as meeting traffic management initiatives or standard procedure requirements. As well, variability in the speeds and altitude behaviors (e.g. climbs or descents) of aircraft within the flow can increase the coupling between aircraft operating within the structure of the sector.

In the congestion mode, controller attention is directed towards managing the interactions between aircraft conforming to the flow structure. Controllers remove some aircraft from the standard flows in order to relieve the excess demand. Many of these aircraft require some form of buffering in the form of path stretching or holding. As a result, some aircraft will experience significantly more inefficient routes as controllers attempt to maintain control of a situation; the impact of these actions can be observed in the average inefficiency per aircraft.

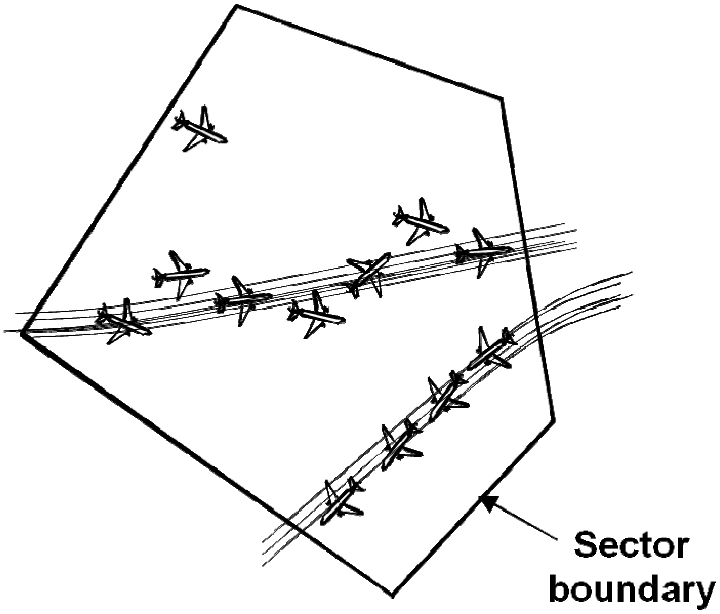

Figure 6–23. Congestion operating mode.

6.7.4 Mode 4 – System Shock

A fourth mode also appears to be used, though infrequently. A system shock mode, corresponds to cases where a sudden change in the external conditions forces the controller to quickly create contingency plans. Such shocks can occur through sudden changes in weather such as pop-up thunderstorms, emergencies, or downstream sectors unexpectedly refusing to accept handoffs (see Figure 6–24). Under such conditions, the pre-existing route structure may become unusable or irrelevant. In many cases, such a shock can be akin to a sudden forced transition to the opportunity mode, requiring pair-wise comparisons that can quickly overwhelm a controller.

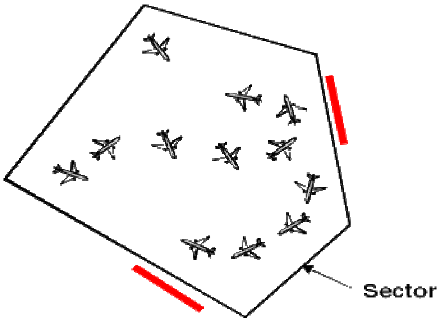

Figure 6–24. System shock operating mode.

6.8 Mode Transitions

A shift between different operating modes leads to observable changes in controller behavior and system performance. This provides an opportunity for investigating controller complexity management by observing changes in system performance. For example, by observing variations in the average distance flown by aircraft, changes in the use of standard flows and by extension use of the standard flow abstraction, can be observed.

It is hypothesized that transitions between operating modes occur in response to complicated internal assessments of the controller's current perceptions of complexity, workload, fatigue and other factors. Notionally, controllers are expected to transition to easier, less complex modes of operation, as their perceived complexity approaches internal tolerance limits. These limits will be subjective, individual, and likely fuzzy and ill-defined. The notional process is illustrated in Figure 6–25. As the load or traffic level increases, a controller can switch to a mode that reduces the perceived complexity and maintains it below the threshold.

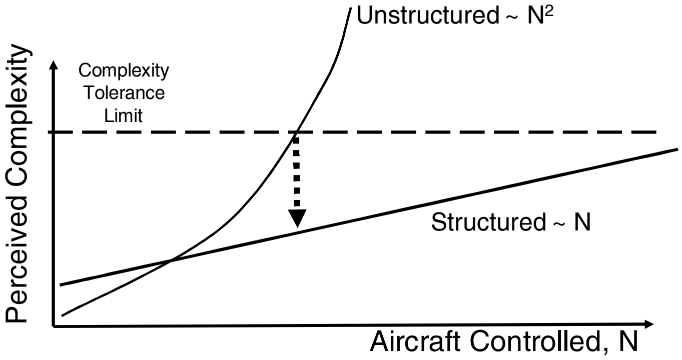

Figure 6–25. Shifts to alternative modes may allow controller to maintain perceived complexity below a notional tolerance limit.

Transitioning to a new mode changes the strategies, techniques, and working mental models used by the controller, reducing the perceived complexity. Such mode transitions allow the controller to operate at higher traffic levels. For example, in the opportunity mode the perceived complexity will likely scale with the square of the number of aircraft, N, due to the predominant strategy of pair-wise comparisons. The resulting unstructured system may produce a perceived complexity above the controller's "Complexity Tolerance Limit" as traffic volume increases. In contrast, switching to a route structure mode allows controllers to use strategies that take advantage of standard flows to reduce the order of their working mental model, reducing the Cognitive and perceived complexity. As a rough approximation, in such a structured operating mode, the perceived complexity scales linearly in the route structure mode as each aircraft only has to be checked with the aircraft next to it.

6.9 Summary

The examples of structure-based abstractions presented in this chapter simplify a controller's cognitive processes in multiple, often overlapping ways. A key mechanism, common to multiple abstractions, is reducing the order of the problem. The use of structure-based abstractions appears to be dynamic and responsive to changes in the number of aircraft being controlled.

CHAPTER 7 Experimental Probes of Structure-based Abstraction Mechanisms and Controller Operating Modes

The observations and evidence leading to the identification of structure-based abstractions and the development of the operating mode hypothesis were obtained primarily from rich but uncontrolled settings. In order to investigate the effects of directly manipulating the structure of an air traffic situation, and the effects of manipulating traffic levels on the use of structure, two part-task human-in-the-loop experiments were conducted. Part-task experiments offer the ability to focus on particular aspects of the influences of structure in more controlled, replicable settings and observe behavioral differences in response to controlled manipulations of the operational environment.

The first experiment investigated the effects of directly controlling the presence of structure supporting standard flow and critical point abstractions. As identified in Chapter 6, one of the key mechanisms by which standard flow abstractions are hypothesized to simplify working mental models is the reduction of the order or degrees-of-freedom in the working mental model. To explore this mechanism, an experiment was conducted that explicitly modified the degrees-of-freedom of an air traffic situation by manipulating the presence of standard flows. This "degrees-of-freedom" experiment is described in Section 7.1.

The second experiment probed more deeply into the dynamic use of structure-based abstractions. It explicitly explored the effects of varying traffic levels on the use of structure. A single environment with consistent structure was created. The effects of varying traffic levels on the use of that structure was observed. It was hypothesized in Chapter 6 that increases in cognitive complexity should produce distinct and observable differences in the use of the structure in the airspace as controllers transition between distinct operating modes. The goal of the experiment was to demonstrate that changes in traffic levels produce changes in the use of structure, consistent with transitions between distinct operating modes. Section 7.2 describes this "operating mode" experiment.

7.1 “Degrees-of-Freedom” Experiment

The first human-in-the-loop part-task experiment manipulated the presence of standard flows in an air traffic situation in order to create three distinct traffic configurations each with a differing structure. The manipulations of the standard flows had the effect of varying the number of degrees-of-freedom that would be required in a working mental model to represent the potential problem space, or region where conflicts could be expected to occur. In order to investigate the effects of such manipulations and the consequences of reducing the order of a situation, the experiment probed strategies and performance on a conflict detection task for each of the three traffic configurations.

7.1.1 Experiment Design

A simple part-task ATC simulation was created and the configuration of aircraft through the simulated sector varied. In all cases, aircraft entered from either the left edge or bottom edge of an idealized radar display and travelled on a constant heading to the same point on the opposite edge. All aircraft were, and remained, at a constant, common, altitude.

The order of the problem was varied by controlling whether the set of aircraft entering at each edge were consolidated into a standard flow. As shown in Figure 7–1, this resulted in three distinct configurations where aircraft conflicts could occur: at a single point, somewhere along a line, or somewhere within an area.

Each configuration has a different number of dimensions in the space where potential conflicts could occur. If both sets of aircraft are in flows, potential conflicts can only occur at a single point, as shown in Figure 7–1 (A). This forms a critical point and reduces the problem space to a single dimension. In contrast, if neither set of aircraft is in a flow, Figure 7–1 (C) shows how potential conflicts can occur anywhere over a two dimensional spatial region, and at any time, yielding a problem space with 3 dimensions (x, y, time).[30] Figure 7–1 (B) illustrates the case where only one set of aircraft is in a flow. The shape of the region of possible conflicts is a line and, as conflicts can occur at any time, the resulting problem space has two dimensions.

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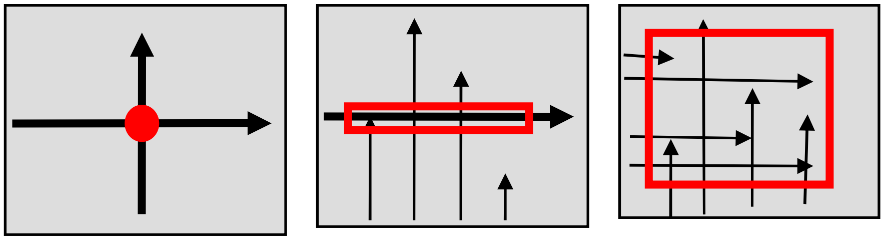
[30] A conflict between a pair of aircraft will occur at a well-defined space-time point but the locus of possible conflict points will trace out an area.



Point
(A)

Line
(B)

Area
(C)

Figure 7–1. Traffic configurations for Degrees-of-Freedom experiment

Task

Participants monitored several minutes of traffic through the simulated sector, identifying any conflicts as they occurred. On detecting a conflict participants pressed the space-bar on the keyboard in front of them. Participants were instructed to only indicate a conflict when they felt sure that, as the controller, they would have to take some action to "move" one of the aircraft involved.[31]

Upon indicating a conflict, the simulation would freeze; participants used a mouse to select the two aircraft that they believed were involved in the conflict. Participants could select only two aircraft at a time. Pressing a "Continue" button located on the right edge of the display resumed the simulation. Participants received feedback on their performance as aircraft that were involved in a conflict turned red at the initial violation of the separation minima. Approximately 3 seconds later the aircraft were removed from the display.

Apparatus

A simplified ATC simulation environment was built using the Visual Basic .NET framework. The simulation environment allowed the creation of a simple radar screen on which aircraft positions, history, and data blocks could be displayed. A closeup view of the radar display is shown in Figure 7–2.

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[31] It was stressed to participants that the relevant criterion was "knowledge" that the controller would have to take *some* action, not when that action would occur. This was an attempt to control for participants using resolution strategies with different lead-times (e.g. timing of turns vs. altitude changes etc…).

The current position of each aircraft was depicted by an ‘x’ and the previous four displayed positions were indicated with a slash “/”. Around each ‘x’ a circle of radius 2.5 nautical miles was drawn indicating half the required minimum separation distance. Thus, two aircraft would be in conflict if their respective circles touched.

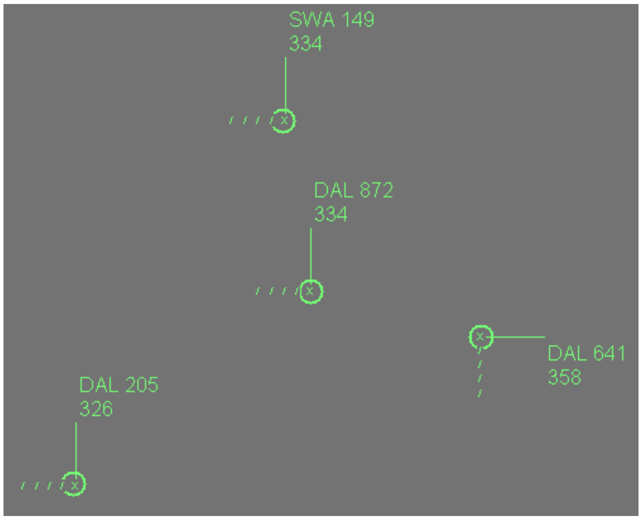

Figure 7–2. Aircraft position, history and data blocks as displayed in the simulation.

Associated with each aircraft was a data block. The first line of the data block displayed an identifying code in the form of an airline and flight number combination. The second line displayed the aircrafts ground speed in knots (nm/hr). Some concerns were raised by participants about the placement of data blocks and the potential for overlapping tags to cause interference. The scenario design process attempted to minimize such situations but inevitably some overlapping did occur. This was considered acceptable as the effect is reflective of operational reality and is a daily challenge for air traffic controllers.

The radar screen simulated a square sector measuring 200 nm by 200 nm. The screen was updated at 2 Hz. In order to create a reasonable pace of events without overloading participants, all simulation events occurred at 50 times real-time speed. Aircraft took approximately 45 seconds to cross from one edge of the screen to the other. These values were validated as generally acceptable to users through pilot testing.

Scenario Design

The configurations of traffic in Table 7–1 defined the independent variable for the experiment. In order to ensure that the experiment tested differences in the degrees-of-freedom in the problem space, scenarios for each configuration were carefully designed to be as equivalent as possible.

Each scenario contained 6 conflicts, identified as C1 – C6. To prevent participants from deducing a particular location that all conflicts would occur at, conflict locations were varied throughout the possible regions of each scenario (see Table 7–1). All conflicts occurred at the center point of the display in the Point scenario. The order of conflicts within each scenario was fixed and the same for all participants.

Table 7–1. Conflict locations in each scenario.

Conflict:	Point	Line	Area
C1	**Middle Centre**	**Middle Left**	**Top Right**
C2	**Middle Centre**	**Middle Centre**	**Middle Right**
C3	**Middle Centre**	**Middle Centre**	**Middle Centre**
C4	**Middle Centre**	**Middle Centre**	**Bottom Left**
C5	**Middle Centre**	**Middle Left**	**Top Centre**
C6	**Middle Centre**	**Middle Right**	**Middle Centre**

Each scenario contained 52 aircraft. The need to control the number and relative spacing of conflicts precluded the use of a standard template and simple geometric shifts. The Point scenario was designed first. Arrival times at the sector boundary were assigned to each aircraft. Speeds were randomly assigned to each aircraft within the range of 330 +/- 50 knots. From this baseline, the 6 conflicts were 'induced' into the scenario by varying the relative entry times and adjusting aircraft speeds.

The resulting Point scenario formed the basis for the Line scenario. Each aircraft traveling from the bottom edge to the top edge was randomly assigned an entry position along the bottom edge. In order to avoid conflicts occurring immediately upon aircraft entry, entry positions within 20% of the screen width on both the left and right edges were excluded. Aircraft entry times and relative speeds were further adjusted to ensure that only 6 conflicts occurred. The Area scenario was derived from the resulting Line scenario by applying the same procedure to the aircraft entering from the left edge.

The following additional conditions applied to all scenarios:

- No aircraft changed speed at any time during any scenario
- Only one aircraft involved in any subsequent conflict could be onscreen at the time of a conflict (e.g. only one pair of conflicting aircraft could be on screen at a time)
- All aircraft that were not in conflict had a minimum separation at the point of closest approach of 15 nm.

Efforts were made to ensure that the scenarios were as similar as possible except for the variance introduced by the independent variable. The same average rate of aircraft for each direction of travel was used in all scenarios (~ 6.5 aircraft / minute). As well, during each scenario the number of aircraft instantaneously onscreen varied across the same range of 6-12 aircraft. The number of aircraft on screen at the time of a conflict was kept constant across scenarios within the range of 9 +/- 2 aircraft.

Participants

Twelve participants were recruited from the graduate student population of the Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology. Participants were predominantly male (~ 80%), and ranged in age from 23 – 42. Two air traffic controller trainees and a professional pilot participated in pilot tests using a preliminary form of the standard pre-experiment training protocol. While their results are not reported in the analysis below, similar behavior to that found for the graduate student population was observed.

Procedure

Participants initially completed a consent form and pre-test questionnaire collecting demographic data. Participants were then provided with a written set of instructions describing the experimental task. A series of training exercises was used to ensure their proficiency with the task and the experiment apparatus.

Participants were explicitly instructed that:

- There were no conflict situations occurring at the beginning of each scenario
- Aircraft would either lose separation or miss by 15 miles or more.

The second condition was set in order to ensure that the criteria for detecting conflicts was clear and participants were not attempting to judge conflicts with miss distances that were beyond the resolution capabilities of the simulation system (for example 4.8 vs. 5.2 nm).

Each participant completed three trials, one for each scenario. Each trial was approximately 4 minutes in length. In order to account for fatigue, learning and other potential confounds, the order of presentation of scenarios was counterbalanced across participants.

At the beginning of the first scenario, participants were asked to think aloud as they performed the conflict detection task. Comments were written down by the experiment administrator. Following each scenario, participants were given a short questionnaire to obtain subjective feedback on the relative complexity of the scenario and to identify strategies used during it. After completing the questionnaire for the third scenario, participants were given a post-test questionnaire asking them to identify the easiest and most difficult scenarios.

7.1.2 Results

Several measures were used to compare participants' performance in each traffic configuration. The primary performance measure was each participant's ability to anticipate conflicts. Data were also collected on errors of omission (missed conflicts) and commission (identified conflicts that were not an actual conflict). Participant comments collected as part of the think aloud protocol, post trial, and post experiment questionnaires were analyzed in order to assess participant use of standard flow abstractions and to collect subjective assessments of the complexity of each scenario.

Conflicts Identified Earlier in Point Scenario

Simpler working mental models should be quicker, easier to use, and lead to earlier anticipation of potential conflicts. The "time-to-conflict" variable, illustrated in Figure 7–3, captured how early a subject was able to recognize a situation that would require some control intervention. To compare performance differences between the configurations of aircraft, the average time-to-conflict across the six conflicts in each configuration was computed for each participant.[32]

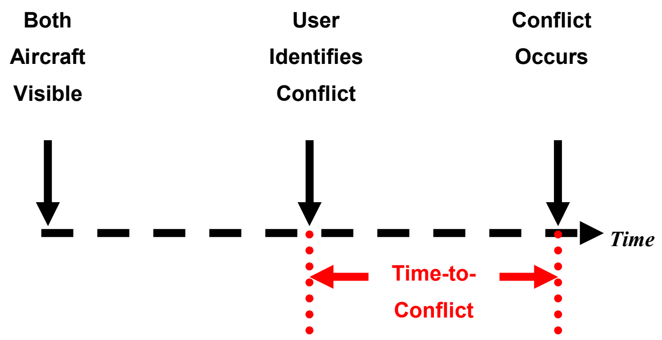

Figure 7–3. Primary dependent variable: "Time-to-conflict".

For each configuration, the average time-to-conflict across participants is shown in Figure 7–4. Error bars indicate the standard error in the mean as computed across participants. Examination of the variance between scenarios showed a lack of homogeneity between scenarios. Therefore, a

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[32] Conflicts that the subject did not detect were assigned a time-to-conflict value of 0 seconds.

mixed linear model with unstructured covariance matrix estimate for repeated measures was used to analyze the time-to-conflict dependent variable. The results showed a statistically significant difference amongst the three configurations F(2,11) = 19.2, p = 0.0003. Follow up multiple comparisons using Scheffe adjustments to control the inflation of Type I errors found significant differences between all configurations. Specifically, significant differences were found between Point-Line (t(11)= 3.76, p = 0.011), Point-Area (t(11) = 5.25, p = 0.001), and Line-Area (t(11)= 3.45, p = 0.018) configurations.

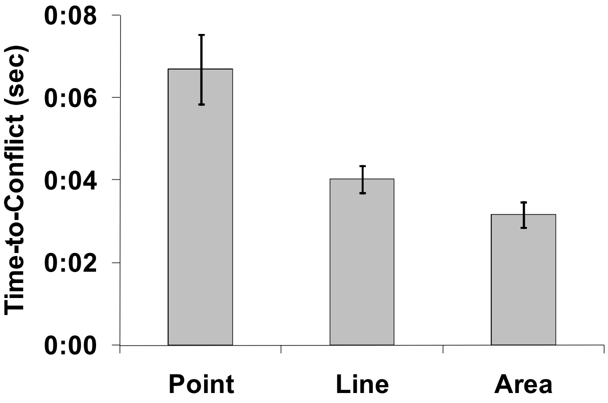

Figure 7–4. **Average time-to-conflict for each configuration of traffic. Error bars show standard errors for the respective means.**

More Missed Conflicts and Incorrectly Identified Conflicts in Area Scenario

Performance was also analyzed in terms of errors of omission and errors of commission. Errors of omission corresponded to missed conflicts; errors of commission correspond to false positives, or cases where a participant indicated a conflict but the two aircraft were not in conflict.

The percentage of missed conflicts in each traffic configuration was determined for each participant. The average number of conflicts missed across participants was computed for each configuration and is shown in Figure 7–5. Errors were more frequent in the Area scenario than either the Point or Line scenarios.

As the percentage of missed conflicts showed departures from the assumptions of normalcy, non parametric Friedman tests were used. A significant difference was found amongst the mean percentage of missed conflicts (χ^2_F = 4.8, p = 0.018). Post hoc multiple comparisons were performed using the least significant difference method; results showed a significant difference between the Point and Area configurations (t(11) = 9.0, p = 0.006).

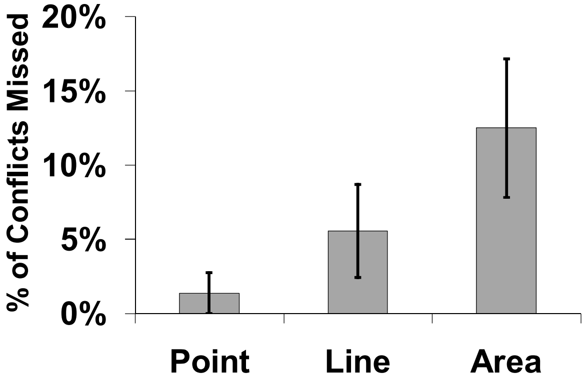

Figure 7–5. **Missed conflicts.**

Participants could indicate a conflict was going to occur even though the aircraft were not in conflict. A count was made of the number of times a participant paused the simulation and incorrectly identified a pair of aircraft as being in conflict. As shown in Figure 7–6, these errors of commission were also more frequent in the Area scenario than either the Point or Line scenarios.

Consistent with the figure, a repeated measure ANOVA found a significant difference amongst the mean number of incorrectly identified conflicts (F(2,22) = 4.2, p = 0.029). Single-sided follow up matched sample t-tests found a significant difference between the Point and Area conditions (t(11) = 2.39, p = 0.017).

As the number of incorrectly identified conflicts also showed departures from the assumptions of normalcy, non-parametric Friedman tests were used. Consistent with the figure, a significant difference was found amongst the mean percentage of incorrectly identified conflicts ($\chi^2_F = 5.9$, p = 0.009). Post hoc multiple comparisons were performed using the least significant difference method; results showed a significant difference between the Point and Area configurations (t(11) = 9.0, p = 0.003) and between the Point and Line configurations (t(11) = 6.0, p = 0.035).

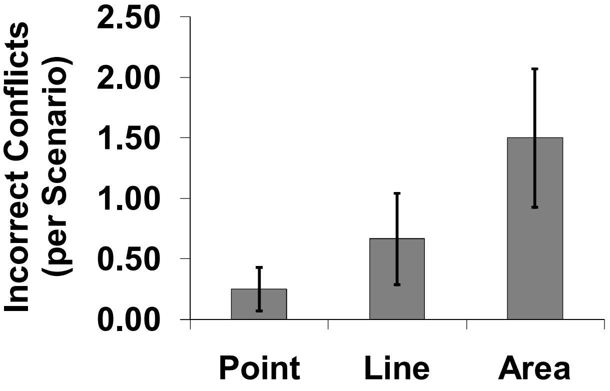

Figure 7–6. Incorrectly identified conflicts.

Area Scenario Identified as Hardest

Post trial and post experiment questionnaires probed participants' subjective perceptions of the relative difficulty of each configuration of traffic. After completing all three configurations, participants were asked to identify the scenario they found easiest and the scenario they found hardest. Chi square tests on the proportion of participants identifying each configuration were both significant (easiest: $\chi^2(2)= 12.0$, $p = 0.007$, hardest: $\chi^2(2)= 16.7$, $p = 0.0008$). Figure 7–7 shows that most participants identified the Point scenario as the easiest while none identified the Area scenario as the easiest. In contrast, 90% of participants identified the Area scenario as the hardest.

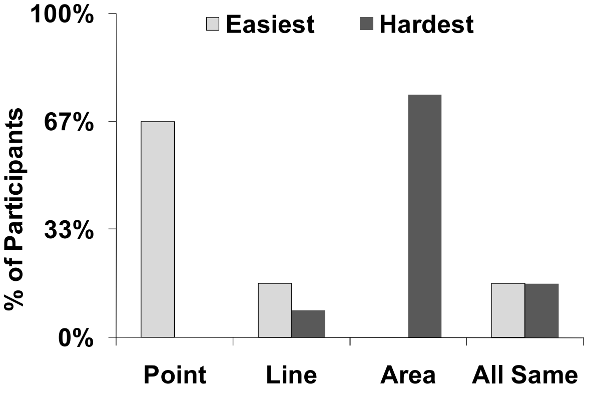

Figure 7–7. Percentage of participants identifying each scenario as the easiest/hardest.

This was consistent with ratings given by participants after each trial. Participants rated how comfortable they were that they could identify all conflicts during that scenario; ratings used an ordinal scale from 1 – 5 where 1 indicated "Not very comfortable" and 5 indicated "Very comfortable." Figure 7–8 shows the distribution of ratings for each configuration. The distributions show participants were much more comfortable identifying conflicts in the Point scenario as compared to the Area scenario.

Participant Comments and Question Responses Support Abstraction Hypothesis

Insight into the effects manipulating the standard flows on the conflict detection task and participant use of standard flow and critical point abstractions was gained by examining the comments made by participants as part of the think-aloud verbal protocol. In addition, responses to post trial and post experiment questionnaires were examined. These questionnaires probed participant strategies in each scenario as well as the factors making scenarios more or less difficult.

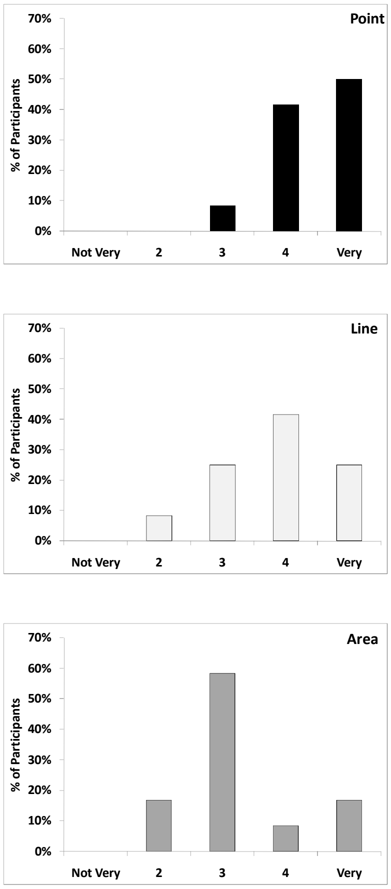

Figure 7–8. “Did you feel you were able to comfortably identify all conflicts in the scenario?”

Data gathered from the think aloud protocol supports the hypothesis that participants took advantage of the presence of standard flows to form standard flow abstractions. Participants made comments consistent with their abstracting aircraft in the situation into a high-level object or flow. Comments such as “this [aircraft] is going to go through here [a hole]”, and “the gap is too big” are consistent with participants building abstractions of standard flows. Such comments suggest participants have abstracted at least pairs of aircraft into a larger unit that was used as the basis for comparisons with another aircraft. Other participants primarily used a pair-wise evaluation strategy as indicated by identifying individual aircraft and describing their conflict status. For example, participants made comments such as: “American four sixty seven, Southwest five thirty four, that’s going to be all right.”

Though useful in providing insight into the strategies and mental models used by an experiment participant, the think aloud protocol requires participants to remember to articulate their thoughts. As common in many studies, participant compliance with the think aloud protocol was not consistent. This precluded a systematic participant-by-participant analysis of any performance differences between participants whose language suggested the use of a standard flow abstraction and those whose language suggested a pair-wise comparison strategy.

The responses to open-ended questions regarding their use of strategies, factors making a scenario more difficult, and what made a scenario the easiest/hardest were reviewed for statements consistent with the use of standard flow and critical point abstractions. The results support the hypothesized degrees-of-freedom reduction mechanism and suggested additional mechanisms.

The presence of standard flows in a scenario was associated with a reduction in the number of aircraft thought to be in the scenario. Half the participants identified “too many airplanes” as a factor making the Area scenario more difficult in spite of the fact that the Area scenario contained exactly the same number of aircraft in approximately the same amount of time as all other scenarios.

Participant responses provided additional insight into the consequences of the standard flow structure. The responses indicated three particular challenges arose in the absence of standard flows, increasing the difficulty of the task; Figure 7–9 shows the percentage of participants making statements consistent with each challenges.

The most frequently identified challenge was that the need to manage multiple conflict locations. In the absence of standard flows, “collision could occur anywhere” and there were “too many aircraft at some points and different possible conflicts.” In contrast, scenarios where at least one standard flow was present helped reduce the number of locations where conflicts could be expected: “Focus on two zones only on the screen, with only one possible location for conflict.”

A second challenge, cited by close to half of the participants, was the increase in the number of points at which aircraft could enter the scenario. One participant identified the Point scenario as easiest because of the “same location for most aircraft to come into the situation.” This is consistent with the standard flows reducing the number of potential inputs into the situation, reducing the order of the problem.

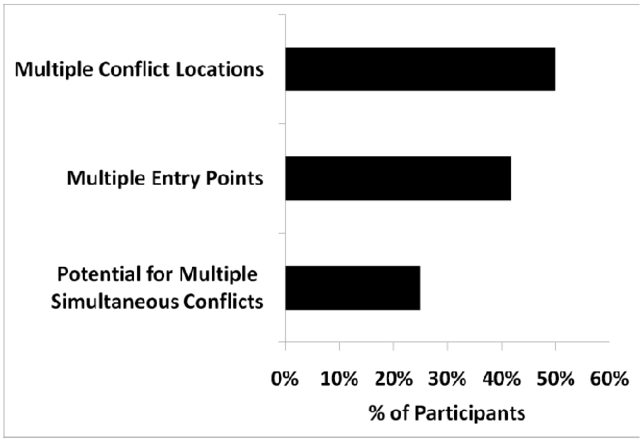

Figure 7–9. Challenges associated with absence of standard flows.

A final challenge was the potential for multiple simultaneous conflicts/events. The Point scenario was easier because "the intersecting stream structure made it simpler to do. Simultaneous near collisions were not possible, so I could pay more attention to the aircraft with near-term possible conflicts." Participants commented that what made the scenario they rated the most difficult hard was the potential for multiple conflicts to simultaneously demand monitoring attention. For example, "[in the Area scenario], the structure made it possible for more than one possible near-term conflict at a time, often far apart."

7.1.3 Discussion of the Results

The results presented above are consistent with the underlying hypothesis that the presence of structure that reduces the degrees-of-freedom in a problem space makes the conflict identification task easier. The reduction in the number of degrees-of-freedom is a direct consequence of manipulating the existence of flows. Objective performance, subjective assessments, participant written comments and think-aloud comments all support this hypothesis.

The presence of standard flows and a single critical point in the Point scenario produced both lower levels of perceived complexity as evidenced by scenario rankings, as well as better performance on the conflict detection task. The lack of structure and increased order of the problem in the Area scenario was associated with increased perceived complexity and decreased performance.

Factors identifying the easiest and hardest scenarios highlighted an additional consequence of the decrease in degrees-of-freedom in the Point scenario. One of the key effects of the standard flows in the Point scenario was the elimination of the potential of multiple conflicts occurring simultaneously. In the Point configuration, it is possible for there to be more than one conflict occurring at any given moment in time. However, the structure eliminates the possibility of those conflicts occurring simultaneously at a point in time in the future. In both the Line and Area scenarios, participants' perceived complexity was clearly affected by the perception that multiple conflicts could occur simultaneously. The structure in the Point scenario eliminated that possibility.

In summary, performance improvements and decreases in participants' perception of difficulty were observed in response to manipulations of the structure. Reducing the degrees-of-freedom of the problem, a hypothesized key mechanism of critical point and standard flow abstractions, resulted in earlier conflict detection, fewer errors, and a decrease in perceived complexity. This result supports the general hypothesis that structure-based abstractions are an important resource for mitigating cognitive complexity.

7.2 "Operating Modes" Experiment

The second area of structure-based abstractions that was probed more deeply was the dynamics of their use. It was hypothesized in Chapter 6 that increases in cognitive complexity can prompt controllers to transition to a different operating mode in order to mitigate that increase and keep cognitive complexity at a manageable level. The use of structure-based abstractions in an operating mode is expected to depend on the required level of cognitive complexity mitigation. Understanding when and how controllers transition between these operating modes will provide further insight into the role that structure-based abstractions play in reducing and managing cognitive complexity.

In order to investigate the use of different operating modes, a part-task experiment was conducted. In order to prompt variations in the level of cognitive complexity experienced by participants, traffic loads were manipulated. The goal of the experiment was to demonstrate that changes in traffic levels produce changes in the use of structure, consistent with transitions between distinct operating modes.

An interactive ATC-like task was designed to provide opportunities to observe the use of multiple operating modes and transitions between them. The simulation environment was designed to capture the most relevant elements of ATC without being so realistic as to require excessive amounts of training for participants.

Participant actions were examined with respect to hypothesized changes in the use of standard flow and critical point abstractions and transitions between controller operating modes. The commands used will reflect differences in the use of the underlying structure. The resulting performance, in terms of the efficiency of aircraft trajectories (e.g. distance flown) and success at the task (e.g. errors), are additional observables expected to vary with changes in operating mode.

Based on the expected use of standard flows and critical point abstractions in the Opportunity, route structure, and congestion modes of operation, a simple underlying route structure and set of standard flows was generated (see Figure 7–10). Aircraft entered the sector through two standard flows on the left edge of the screen. After converging on a merge point, all aircraft exited at the right edge of the screen at the point marked “C3.” All aircraft were at the same altitude which participants could not change. The route structure was designed to provide opportunities for participants to bypass the critical point and provide aircraft “shortcuts” if they were operating in an opportunity mode. The rate of aircraft entering the situation was varied and included levels designed to saturate the capacity of the route structure, consistent with congestion mode.

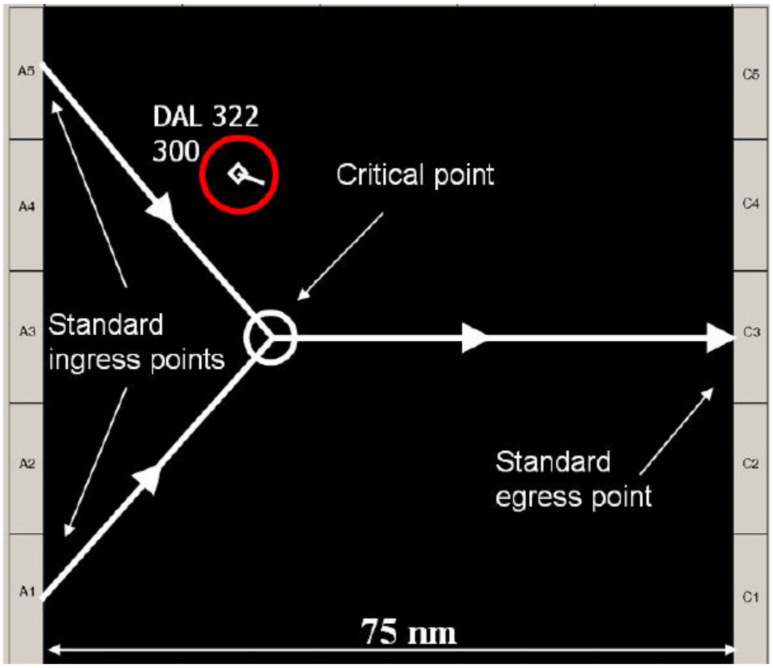

Figure 7–10. Airspace used in Operating Modes experiment.

7.2.1 Experiment Design

Task

There were three primary objectives that participants were instructed to meet in the following order of priority:

- ***Safety:*** maintain the minimum separation standard of 5 miles-in-trail,
- ***Metering:*** aircraft must exit at point C3 10 miles-in-trail and at 300 knots,

- ***Efficiency:*** Offer and respond to requests for “shortcuts.”

The minimum separation standard was represented by circles drawn around each aircraft. Participants heard a loud beeping noise and a large flashing red conflict sign on the right side of the display whenever there were any aircraft in a loss of separation. There was no anticipatory/predictive conflict alert functionality providing feedback to participants.

The metering objective was included to provide opportunities to observe behavior when traffic demand exceeded the physical capacity of the structure. Waypoints were placed at 10 nm intervals in order to provide guidance on the relative spacing of aircraft.

Participants were also reminded of the high cost of fuel and encouraged to respond to any requests for “shortcuts.”

Scenario Design

Each participant performed the task for a common scenario containing 84 aircraft. Aircraft entry times, entry point (e.g. “A1” / “A5”), and initial speeds defined the scenario. The number of aircraft present in the sector was varied by changing the rate at which aircraft entered at the points “A1” and “A5” (see Figure 7–12). The rate for both entry points was the same and remained constant for short periods of time. The variation of the aircraft entry rate established a nominal profile of the number of aircraft controlled over time. However, as the simulation environment was interactive, participant actions introduced small differences in the exact profile of number of aircraft vs. time. An example of the resulting profile for one participant is shown in Figure 7–11.

Aircraft entry rates were selected to vary the total number of aircraft being controlled over a wide range including both very low traffic count situations and very high traffic count situations. The peaks and valleys in traffic count were chosen to vary the load and stimulate use of multiple modes. The peak values were chosen at a level such that the metering requirements were impossible to meet without removing aircraft from the standard airway flows.

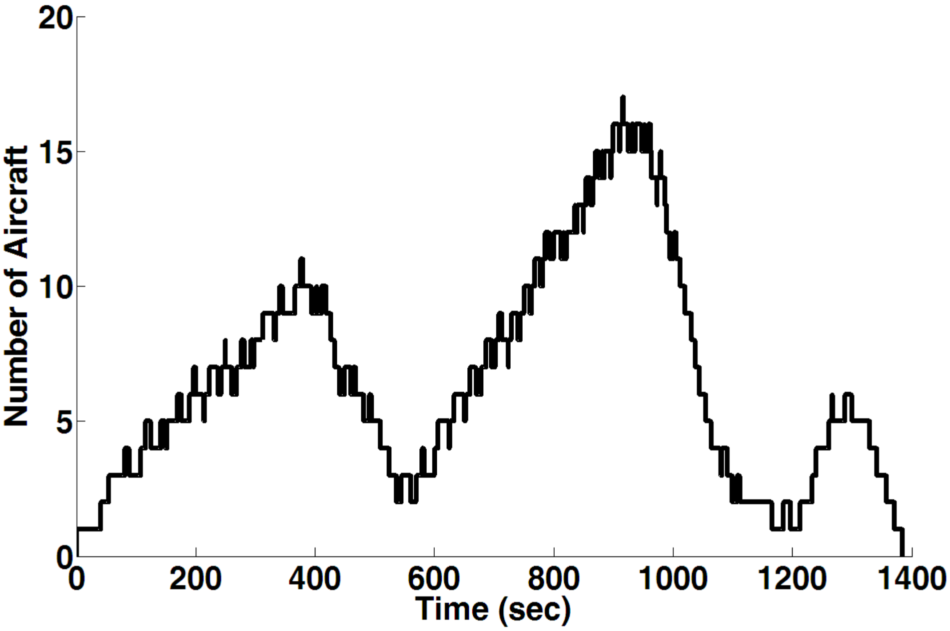

Figure 7–11. **Example profile of number of aircraft as a function of time in scenario.**

The scenario was designed by establishing an absolute phase between aircraft arriving in the upper and lower flows. Through the introduction of slight offsets sampled from a standard distribution, the entry times of individual aircraft were slightly shifted. This was done in order to avoid two unrealistic extremes: perfectly synchronized arrival along the flows, or having every pair of entering aircraft be in conflict. Approximately 38% of the aircraft that entered the scenario would be in conflict at the merge point if no action was taken. Initial aircraft speeds at entry were developed by sampling from a normal distribution with mean 300 knots and standard deviation of 15 knots. Speeds were rounded to the nearest 10 knots and restricted to falling between 260-340 knots.

Apparatus

The simulation system was adapted from a MATLAB ATC simulation designed by Chris Tsonis, MIT. The radar screen simulated a square sector measuring 75 nm by 75 nm and was updated at 2.5 Hz. In order to create a reasonable pace of events without overloading participants, all simulation events occurred at 10 times real-time speed.

On the display, each aircraft appeared as a diamond surrounded by a circle representing half the minimum required distance between aircraft (Figure 7–12). Overlapping circles indicated that the minimum separation distance had been violated.

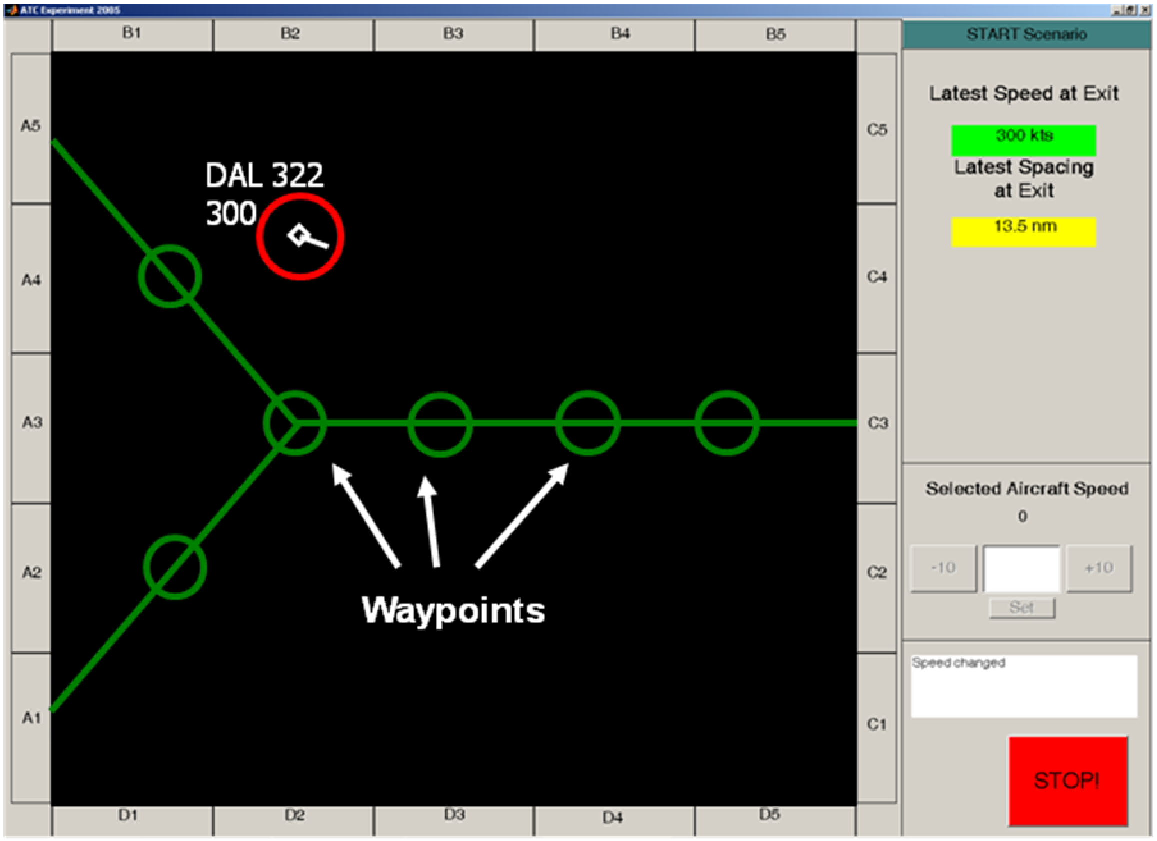

Figure 7–12. User interface for Operating Modes Experiment.

Each aircraft also has a data block with two lines. The first line is an identifier for the aircraft consisting of an airline and flight number. On the second line of the data block is the aircrafts' current speed in knots.

Participants could use both heading and speed commands in order to alter aircraft trajectories in order to meet the task objectives. In the absence of any commands, aircraft would proceed along one of the two paths shown in Figure 7–12. Aircraft were not constrained to the display and could be vectored off screen.

A mousing technique was developed to allow participants to efficiently provide vector commands to aircraft. After selecting an aircraft, a subsequent click anywhere on the screen would cause aircraft to immediately turn and fly on a constant heading toward that point. In order to be consistent with ATC operational practices and the ability to give a command “direct to” a point further along an aircraft’s flight planned route, six waypoints were depicted on the display (see Figure 7–12). If the subsequent click fell within one of the circles representing the way point, the aircraft would fly direct to the way point and, upon reaching it, resume flying along the standard flight path.

The speed of aircraft could be increased and decreased in ten knot increments using buttons on the right side of the display. Finer grain control and large scale changes in speed could also be made by entering an exact value in the area between the buttons. Participants were restricted to assigning speeds within the range 220 to 380 knots.

Feedback on performance on the metering task in the form of relative spacing and assigned speed of the last aircraft to exit was provided at the top right of the display. Requests for shortcuts, check-in announcements, and feedback on recent control actions was provided at the bottom right of the display.

Participants

Fourteen participants completed this experiment; ten were undergraduate or graduate students from the Aeronautics and Astronautics department and four were ATC trainees. The use of controllers as participants gives greater confidence in the results as they are familiar with real-life operations and are likely to be trained to use different strategies under different traffic situations.

Procedure

Similar to the first experiment, participants initially completed a consent form and pre-test questionnaire collecting demographic data. Participants were then provided with a written set of instructions describing the experimental task including the objectives and their order of priority. Two training exercises were used to ensure their proficiency with the task and the experiment apparatus before the participant completed the scenario.

7.2.2 Results

Participant actions and the resulting aircraft trajectories were recorded as part of the simulation system. Multiple performance indicators were computed and analyzed. As noted above, the simulation system was interactive and thus each participant's actions created slight differences in the profile of the number of aircraft in the scenario. Consequently, not all participants experienced the same peaks in traffic levels. The results presented below are restricted to those traffic levels that all participants experienced, namely traffic levels between 0 and 15 aircraft.

Excess distance flown per aircraft

Based on the analysis reported by Howell *et al.* (2003) excess distance was used as the primary observable for identifying the use of an operating mode. For each aircraft the difference between the flight path distance travelled and the distance along the standard route structure was computed. This difference was used to categorize each aircraft into one of the three categories shown in Figure 7–13.

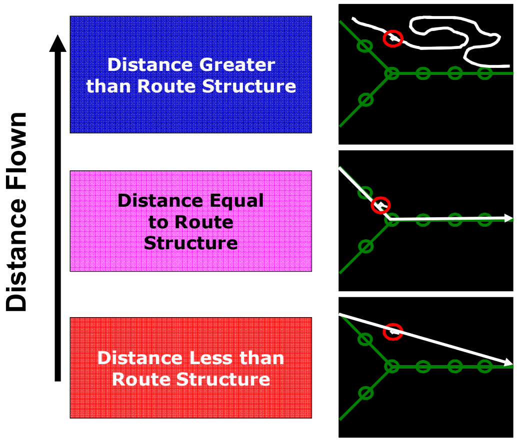

Figure 7–13. Categories of distance flown.

For each participant, the number of aircraft under control, and percentage of aircraft in each of the categories in Figure 7–13, was determined at each time step in the simulation. Time steps with a common number of aircraft being controlled were identified and used to compute an average percentage of aircraft in each category for each value of the number of aircraft under control.

The results were averaged across all participants and are presented in Figure 7–14 with error bars representing the standard error in the estimates of the mean across participants at each traffic level. The results show a clear drop in the percentage of aircraft being given short cuts as traffic volume increased. At traffic levels of about six aircraft, the proportion of aircraft being given a short cut drops below the number of aircraft remaining on the route structure.

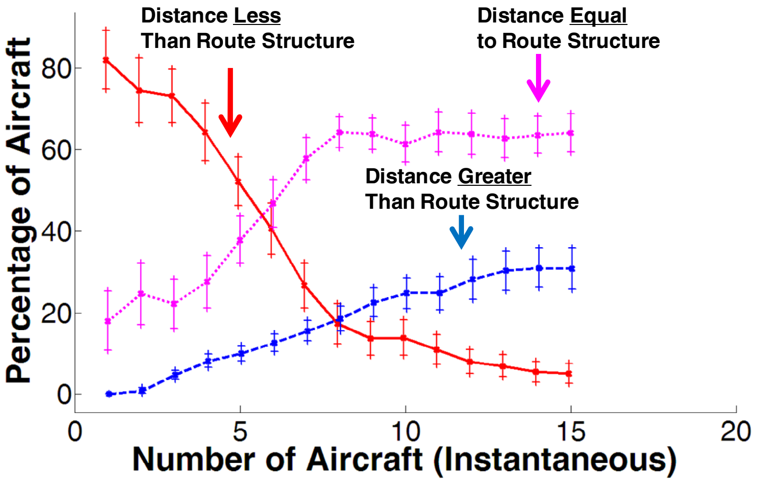

Figure 7–14. Percentage of aircraft in route structure distance category as a function of traffic level.

The proportion of aircraft remaining on the route structure remained approximately constant at sixty percent for traffic levels between eight and fifteen aircraft, while those given short cuts dropped to 15% or less. Above ten aircraft more than one in three aircraft were travelling a distance greater than the route structure.

Commands

Direct measures of participant behaviors were also analyzed. Participants could influence the situation by issuing speed or heading commands. The commands given by each participant were tracked and the rate at which each type of command was given was determined for each traffic level. Averaged over all participants, Figure 7–15 shows the commands per minute observed for both speed and heading commands. Error bars represent one standard error across participants.

At all traffic levels, participants used more speed commands than heading commands. The rate of speed commands rises between 1 and 6 aircraft before reaching a plateau between 6 and 10 aircraft. Beyond 10 aircraft, the use of speed commands drops. Heading commands follow a similar pattern at low traffic levels, rising linearly between 1 and 5 aircraft. A brief plateau between 5 and 7 aircraft is followed by increasing use beyond 8 aircraft.

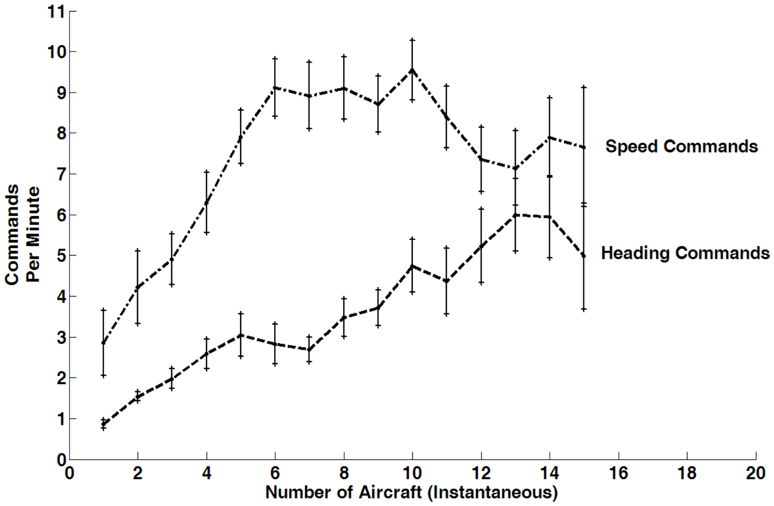

Figure 7–15. Speed and heading commands.

Heading commands were further broken down into commands that used the waypoint structure, equivalent to "direct to" commands, and those that were open-ended, or non-structured.[33] Figure 7–16 shows the proportion of each type of heading command, as well as the total number of heading commands. The figure shows distinct differences in the types of heading commands given by participants. At low traffic levels, primarily structured heading commands are used, consistent with participants using the waypoints on the route structure to give shortcuts. Beyond 6 aircraft the rate of such structured commands decreases, consistent with the decrease in the proportion of aircraft receiving shortcuts (Figure 7–14). The use of non-structured heading commands rises sharply beyond 7 aircraft. Beyond 10 aircraft over 75% of the heading commands are of the non-structured variety, signaling a distinct shift in participant use of the route structure in their commands.

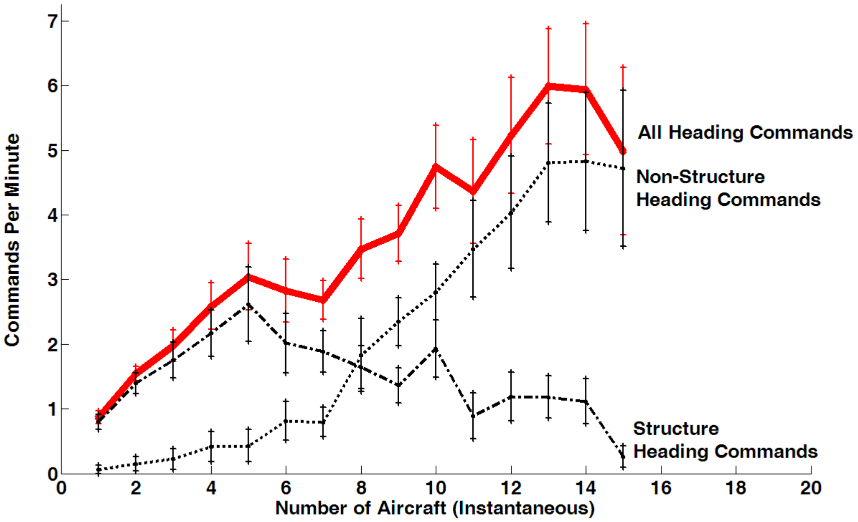

Figure 7–16. **Structured and non-structured heading commands.**

Performance on the metering task objectives

Performance on the metering and separation task objectives was also analyzed. For the metering objective, the participants' task was to ensure that aircraft left the sector at 300 knots and spaced ten miles-in-trail. Aircraft that left the sector with a speed outside of the range of 295-305 knots were scored as a violation of the speed metering requirement. The spacing requirement could be

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[33] For example, a non-structured heading command occurred if a participant clicked anywhere other than within one of the waypoints in Figure 7–12. The aircraft would proceed to the clicked point and continue on indefinitely on the resulting heading.

violated by having aircraft too close together (less than 9.5 miles) or not close enough (between 10.5 and 20 miles). Beyond 20 miles, the aircraft were deemed to be unconnected and hence the spacing requirement did not apply.

For each participant, each aircraft in the scenario was evaluated as to whether it met the metering requirements as it exited the right edge of the display. The proportion of aircraft violating the metering requirements was computed for each simulation time-step. The proportions were grouped by the number of aircraft being controlled and averages computed for each traffic level.

The results presented in Figure 7–17 are averaged across all participants with error bars representing the standard error in the estimates of the mean. The percentage of aircraft violating either metering requirement remains relatively constant below six aircraft. Sharp increases in the metering errors are observable between seven and eleven aircraft. Based on the dimensions of the route and the required metering spacing, the theoretical maximum capacity of the route structure is approximately nine aircraft.

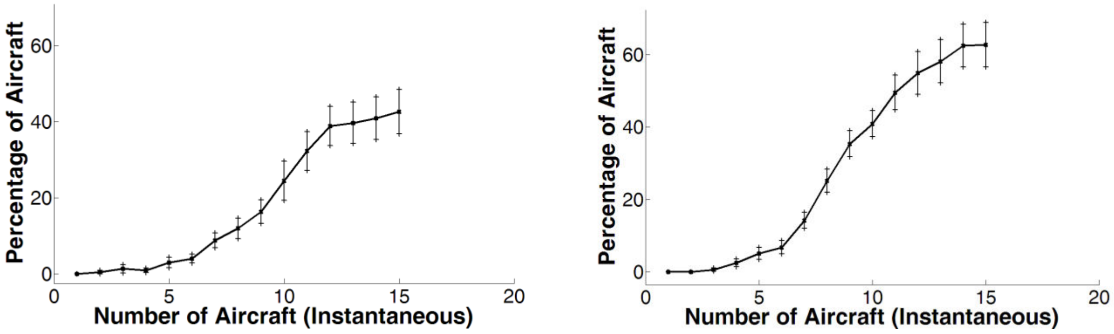

Figure 7–17. **Percentage aircraft violating metering task. Violations of: speed = 300 knots at exit (left), spacing = 10 miles-in-trail at exit (right). Error bars are +/- 1 standard error over participant averages.**

Separation violations of the five mile separation minima

The highest priority task for participants was to maintain safety by ensuring aircraft never became closer than the minimum separation distance. Participants could experience multiple loses of separation simultaneously. In order to take this into account and support comparisons across the range of traffic levels, the number of pairs of aircraft violating the minimum separation standard was computed at each time step for each participant. The average number of pairs of aircraft violating the minimum separation standard was determined for each level of the number of aircraft in the sector.

The results, presented in Figure 7–18, are averages across participants. Error bars represent the standard error in the estimates of the mean across participants at each traffic level. Sharp increases in the losses of separation occur beyond 10 aircraft. This is well below the saturation capacity of the route structure of 17 aircraft.

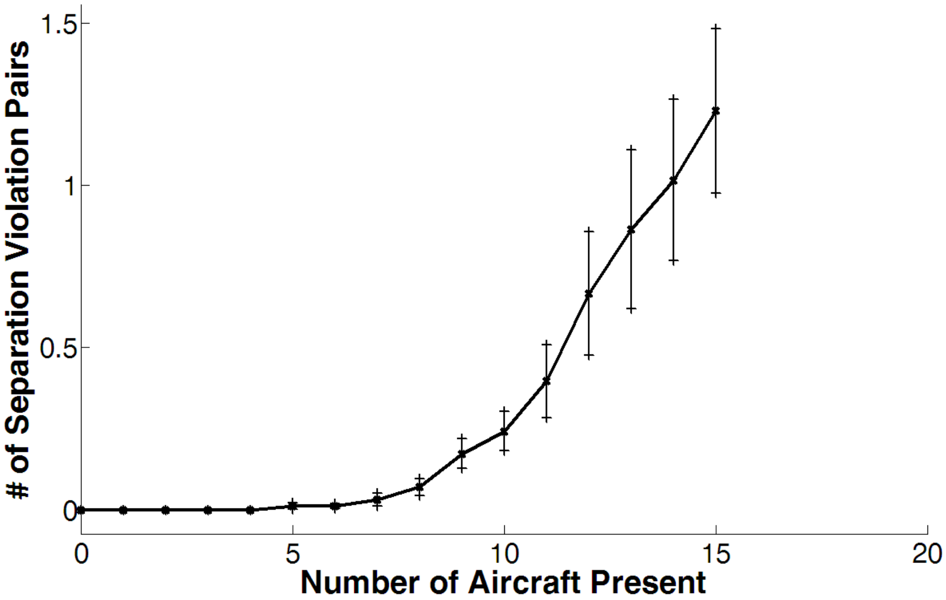

Figure 7–18. Losses of separation as a function of traffic level.

There is a sharp increase in the number of errors at traffic levels of between ten and fifteen aircraft. The results show that, on average, participants had at least one pair of aircraft in a loss of separation event anytime the traffic level rose above 14 aircraft.

7.2.3 Discussion of Results

The results showed participants clearly used the underlying standard flows in the scenario. As hypothesized, use of the standard flows was not homogenous; distinct differences occurred in the use of standard flows, participant commands, and participant performance as the number of aircraft being controlled increased.

No single measurement is a direct indicator of operating in a particular mode; rather, the results were examined for consistency with the hypothesized behaviors and performance discussed in Chapter 6. In order to identify operating modes and transitions between them, Figure 7–19 presents the distance categorization and commands results in a common figure. Regions where participants were likely transitioning between the identified modes are shaded in grey.

As indicated in Figure 7–19, taken together the results are consistent with the hypothesized operating modes. At low traffic levels participants clearly operated in a manner consistent with the opportunity mode. The proportion of aircraft flying equal to, or less than the underlying route structure distance showed a clear transition between participants granting short cuts and leaving aircraft on the standard flows in the sector. Participants used heading commands that took advantage of the waypoints supporting the route structure. This is consistent with the hypothesis that controllers will transition from an opportunity mode to a route structure mode as traffic volume increases. The large gradients in this region suggest this mode transition is relatively strong and well-defined.

Between 6 and 11 aircraft the results are consistent with participants operating in the route structure mode. The proportion of aircraft flying a distance equal to the route structure remained relatively constant. Speed commands are the most common, consistent with participants regulating traffic within the route structure.

Changes in the commands used between 10 and 12 aircraft are consistent with transition to a congestion mode. The use of speed commands declines, and is offset by an increase in the use of heading commands. There is also a sharp shift in the type of heading command used. Above 11 aircraft, the proportion of heading commands that did not use the route structure ("Non-structured" commands) is dominant. The use of "structured" heading commands declines to zero as traffic increased. These changes in command use are consistent with participants operating in the congestion mode. There is also a slight, but discernible, increase in the proportion of aircraft travelling a distance greater than the route structure.

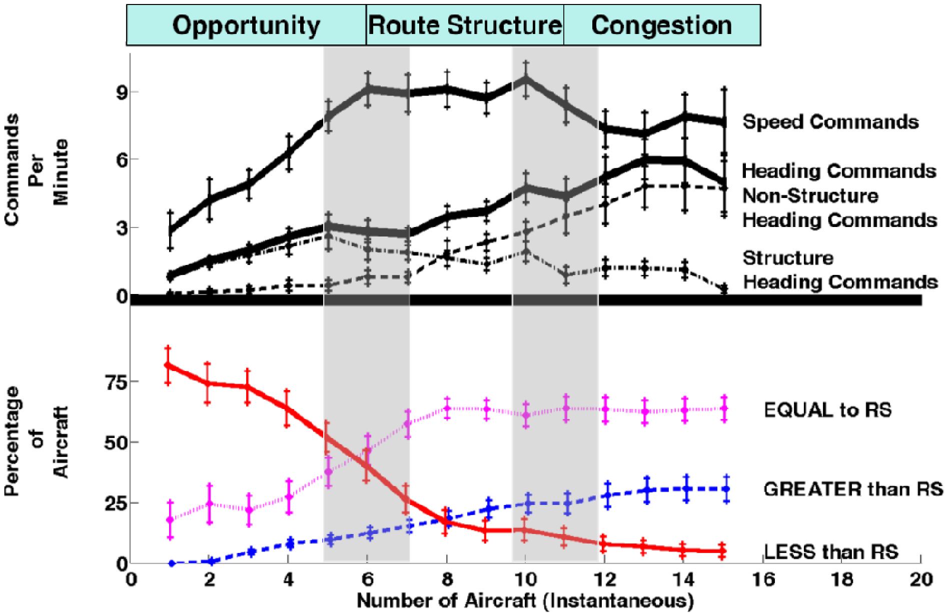

Figure 7–19. Comparison of command rates with aircraft distance flown results and identified modes. Shaded regions indicate mode transitions. (RS = Route Structure).

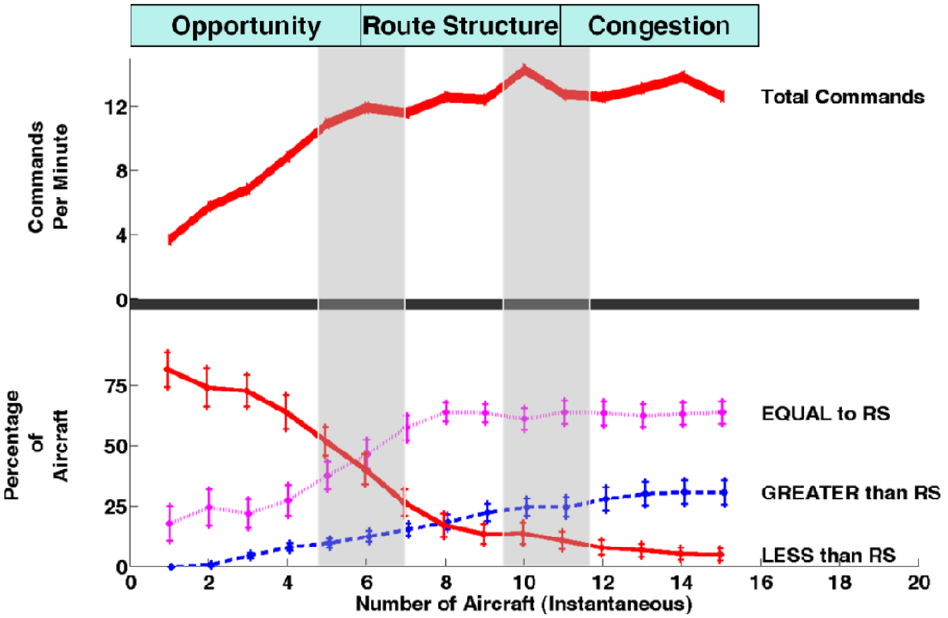

Figure 7–20. Transition from opportunity to route structure mode corresponds to participants reaching a constant total commands per minute. Shaded regions indicate mode transitions. (RS = Route Structure).

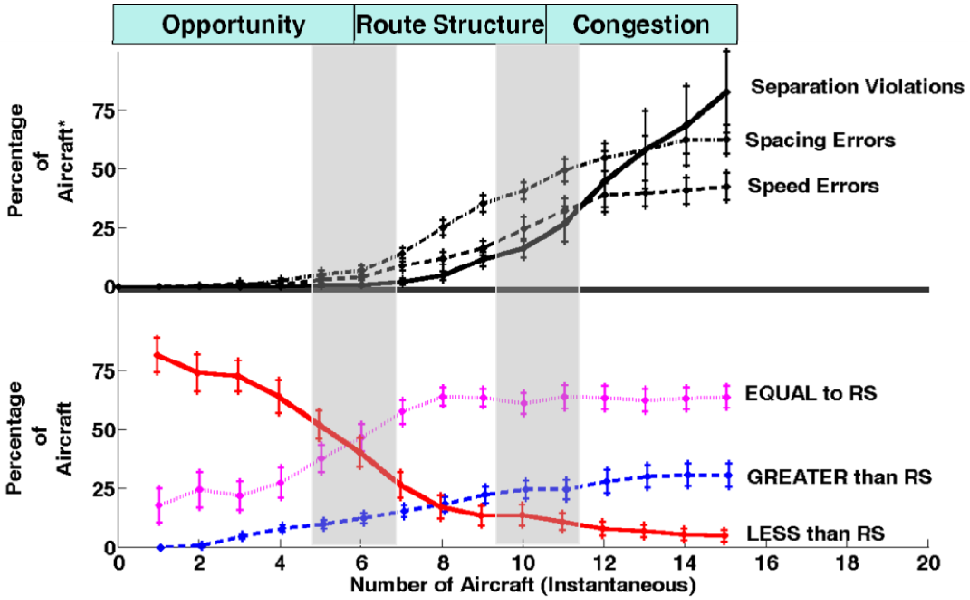

Figure 7–21. Comparison of performance with identified modes. Shaded regions indicate mode transitions. (RS = Route Structure). [34]

Analysis of the transition regions showed two interesting results. Figure 7–20 shows that the transition between opportunity mode and route structure mode occurs at the same traffic level as the start of a plateau in the total number of commands given. The plateau in the total number of commands is consistent with there being an upper limit on the rate at which participants are able to implement commands. Due to limitations of the interface, there were limits on how rapidly participants could identify and implement a particular command.

Performance on the three objectives of safety, metering, and efficiency show minimal changes near the opportunity mode to route structure mode transition (Figure 7–21). This is consistent with the expectation that transitions between operating modes allow controllers to operate at higher traffic levels without impacting performance on the fundamental tasks.

Within the route structure mode, the task performance measures shown in Figure 7–21 provide evidence of progressive task shedding. The spacing metering task is the first shed, followed by the speed metering task and separation tasks. By nine aircraft, the error rate on the metering spacing task has reached 25%, consistent with the traffic level reaching the theoretical maximum capacity of the route structure.

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[34] The # of separation violation pairs was normalized to a scale of 0 -100 in order to present the comparison.

The rapid rise in performance errors is consistent with identification of a transition to congestion mode operations. Performance on the speed metering task objective showed a sharp increase at or about 9 aircraft. Above ten aircraft, separation violation performance rapidly deteriorates. This corresponds to the transition from route structure mode to congestion mode. Such a transition is consistent with participants recognizing their current operating mode is inappropriate and switching to a congestion mode (e.g. pulling aircraft off the route structure) that is more appropriate. Performance on the spacing, speed and separation tasks all stabilize, if at high error rates, immediately after the transition to congestion mode.

The identification of behaviors consistent with the hypothesized operating modes and transitions between them support the hypothesis that controller use of structure-based abstractions is dynamic and responsive to traffic conditions. The traffic levels at which the transitions occurred in the experiment are specific to the experimental conditions, including the configuration of the underlying routes, aircraft dynamics, and participant tasking. Under different conditions, the transitions between modes would occur at different traffic levels.

In summary, the observed changes in the use of standard flow and critical point structural elements in response to varying traffic levels is consistent with the hypothesized transitions between operating modes. Recognizing that structure-based abstractions are used dynamically provides important insight into the tension between capacity and efficiency in the ATC system and informs design opportunities for mitigating this tension. Structure-based abstractions support operation at higher traffic levels, enabling increased capacity. However, the use of these abstractions requires the presence or imposition of structure which can impose efficiency penalties on aircraft trajectories. Designing for variable use of structure that better supports transitions between operating modes may help to mitigate this tension between capacity and efficiency.

7.3 Chapter Summary

Two experiments probing controller use of structure-based abstractions supported a hypothesized complexity reduction mechanism and the dynamic use of standard flow and critical point structural elements. The first experiment explicitly manipulated the underlying route structure and the presence of critical points. The results showed that traffic configurations supporting working mental models with reduced degrees-of-freedom produce lower levels of perceived complexity, as evidenced by scenario rankings, and better performance on the conflict detection task. Participant comments highlighted additional cognitive complexity reduction benefits of standard flows including the elimination of the potential of multiple conflicts occurring simultaneously.

Results from the second experiment provide evidence demonstrating transitions between distinct operating modes. Participants clearly changed how they used the underlying standard flows and critical point as traffic levels increased. Results showed a sharp transition between opportunity mode behaviors and route structure mode behaviors. Distinct changes in the types of commands used provided evidence of a transition from route structure to congestion mode

Recognizing that abstraction use, and the resulting controller cognitive complexity, are dynamic and responsive provides opportunities to modify and introduce new structure that increases capacity and efficiency. Examples of such opportunities are presented in the next chapter.

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CHAPTER 8 Structure-based Abstractions and Cognitive Complexity Considerations in System Design

Structure's central role in simplifying abstraction makes it important to consider how improvements to the design of the ATC system, developed to address delays, inefficiencies, and other performance shortfalls, would affect controller cognitive complexity. Through examining four opportunities to improve system performance, this chapter illustrates how the cognitive process model, structure hierarchy, and an understanding of structure-based abstractions can be used to identify key cognitive complexity considerations that must be considered in system redesign.

8.1 Structure, Airspace Design and Structure-Based Abstractions

New technologies are giving more design flexibility to system and airspace designers at all layers of the structure hierarchy. This is creating opportunities to introduce new forms of structure and make existing ones more effective. Improvements consistent with the mechanisms of existing abstractions will reduce cognitive complexity, enabling more flexible, efficient, and higher capacity operations.

However, proposed improvements to the airspace structure can also disrupt or undermine existing abstractions, and may reveal new limits on system performance. Changes that are inconsistent with existing abstractions can result in poor decision making that leads to errors, and thus raises safety concerns. Poorly-designed structure that would increase cognitive complexity can lead to reduced capacity and/or efficiency as controllers impose their own limits and constraints in order to regulate and manage their cognitive complexity.

Thus, it is important to consider how proposed improvements to the ATC system would change structure and how these changes would impact cognitive complexity. This chapter examines four opportunities to improve the ATC system through structural changes enabled by new technologies. Each example briefly describes a performance shortfall of the current ATC system and one or more related opportunities to address the shortfall. Examples of key cognitive complexity considerations are presented based on an analysis of the impacts of the opportunity on structure-based abstractions, the dynamics, the task and the commands (Figure 8–1). The analyses are not comprehensive and instead focus on illustrating how the cognitive process model, the structure hierarchy, and the use of structure-based abstractions provide valuable insight into cognitive complexity benefits and challenges created by proposed changes to the airspace structure.

The examples presented were selected to cover a range of existing performance shortfalls and challenges associated with introducing new operational concepts; they are not intended to be exhaustive of the possible opportunities to improve the system. Opportunity I examines an opportunity to improve efficiency by optimizing route structures. Opportunity II investigates an opportunity to increase capacity by multi-laning the existing route structure. Opportunity III discusses opportunities to increase robustness by introducing additional waypoints and route definitions to support disrupted operations. Opportunity IV illustrates applying the analysis to 4-dimensional trajectories, expected to be a key part of future concept of operations.

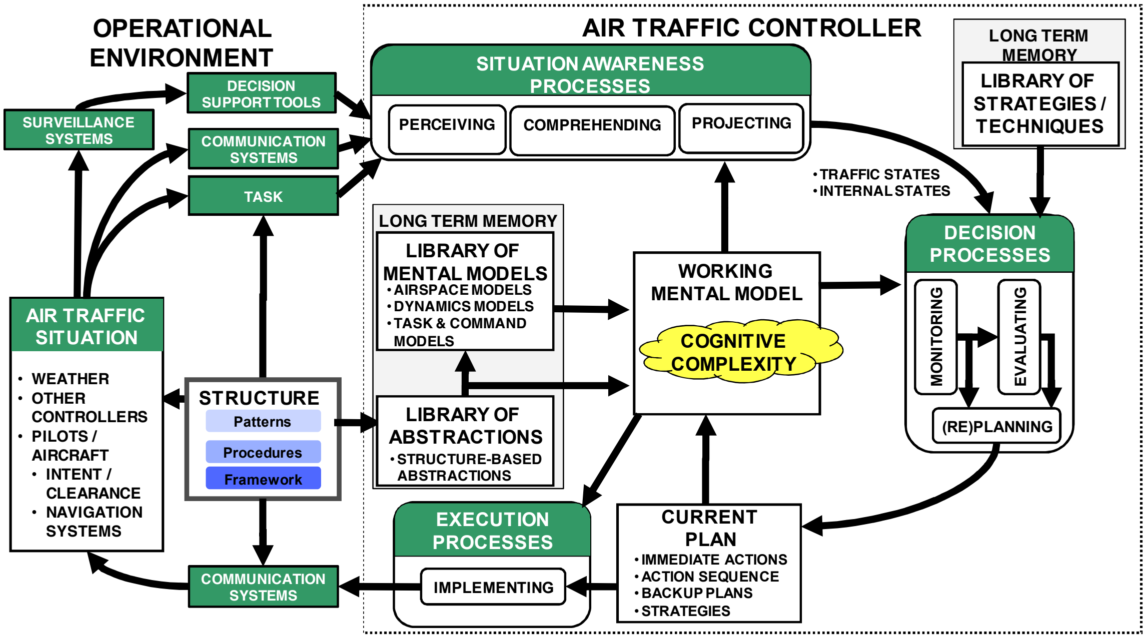

Figure 8–1. Cognitive process model.

8.2 Opportunity I: Increasing Efficiency

The growing recognition of environmental issues and increases in the cost of jet fuel is making the efficiency of aircraft trajectories increasingly important. The design of the route structure is one of, if not the most, significant factor influencing the efficiency of aircraft trajectories. As discussed in Chapters 6 and 7, as traffic loads increase, controllers default to a route structure mode that relies upon aircraft following the underlying route structure. The route structure operating mode spans a wide range of traffic levels, highlighting the importance and potential gains available from optimizing the underlying standard flows (Figure 8–2). Due to the volume of traffic on standard flows, even minor improvements can have significant impacts.

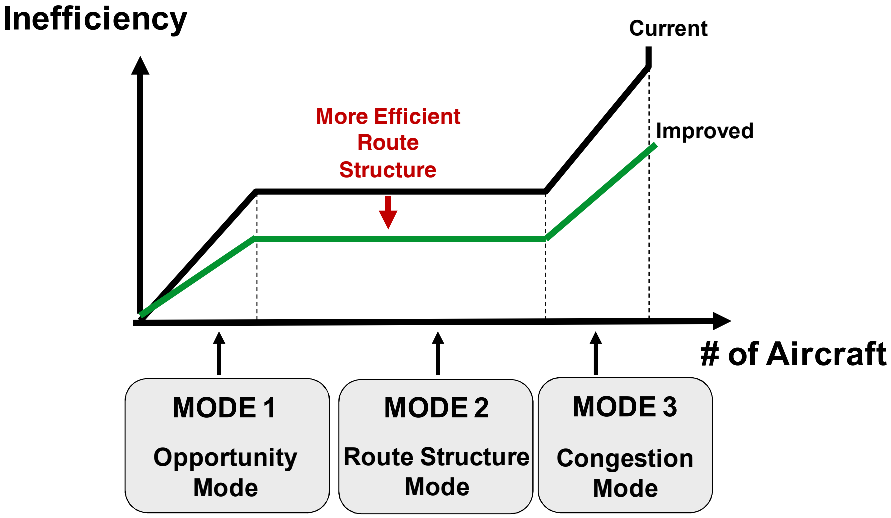

Figure 8–2. Improving efficiency of the route structure.

8.2.1 Opportunities to Optimize the Route Structure

The efficiency of the ATC system has historically been limited by the existing network of VORs. VORs provide navigational guidance only to or from the VOR locations; this fundamentally restricts the underlying route structure and consequently the efficiency and capacity of the ATC system (Figure 8–3).[35] However, satellite-based navigation and other new technologies and capabilities on-board aircraft are enabling new operations concepts, such as Area Navigation (RNAV) and Required Navigation Performance (RNP) operations. In the new operation concepts, the design of location references and route structures are independent of the traditional VOR structure. In RNAV operations, aircraft can navigate directly to/from each RNAV waypoint, greatly expanding the potential paths that can be defined in the airspace. RNP operations allow specification of three-dimensional paths and shift monitoring of conformance to the path to the aircraft. RNAV and RNP operations are still subject to some limitations; for example, some aircraft are limited in the number of waypoints and fixes that can be stored in the onboard databases (Mikolay, 2003).

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[35] Signals from multiple VORs can be used to derive a position. However, additional equipment and capabilities are required to enable navigational guidance based on those positions.

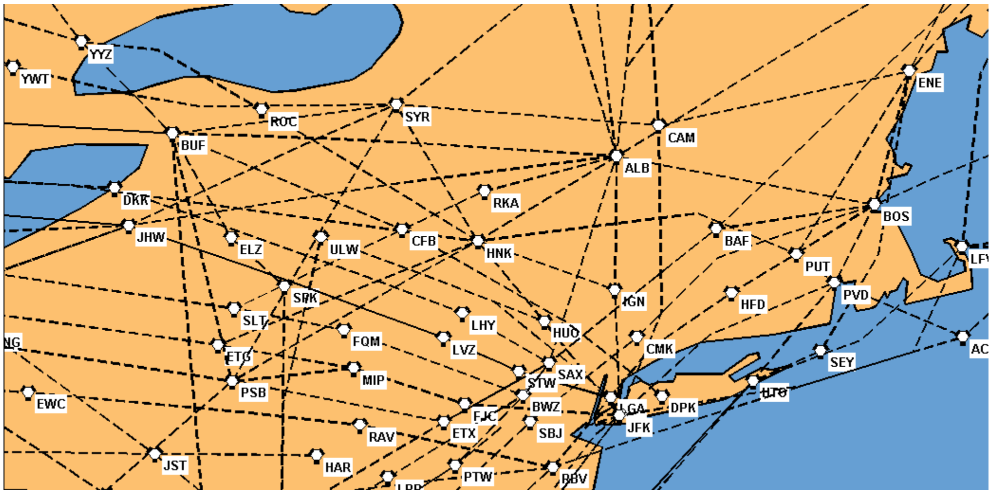

Figure 8–3. VORs and jet routes in north-eastern United States.

The new technologies and operating concepts give more design flexibility to system and airspace designers and provide opportunities to optimize the route structure. New RNAV waypoints can be used to optimize and straighten existing airways and jet routes. Routes that bend due to the limits of VOR navigation can be eliminated, reducing extra distance flown and hence reducing inefficiency. The locations of merge points and crossing points are no longer dictated by the location of VORs and can be optimized with respect to sector boundaries, traffic volumes, and trajectory efficiency. In addition, the paths of airways and jet routes can be optimized around fixed obstacles, such as terrain or Special Use Airspace (SUA) in the operational environment.

8.2.2 Cognitive Complexity Considerations of Optimizing the Route Structure

Where the constraints of VOR navigational have historically limited the efficiency of aircraft trajectories, cognitive complexity considerations are likely to emerge as a limiting factor on the gains to efficiency from optimizing the route structure. Key cognitive complexity considerations can be identified by examining the consequences of optimizing the route structure in the context of the cognitive process model (Figure 8–1).

Optimizing the route structure through moving, modifying, and/or introducing new routes alters the framework layer structure and consequently affects the pattern layer elements higher in the structure hierarchy. In the context of the cognitive process model, the primary impacts of these changes will be on the dynamics of the air traffic situation with important consequences for controller abstractions.

Considerations from Impact on Dynamics and Abstractions

Three examples illustrating the impact of optimizing the route structure on controller abstractions and related cognitive complexity considerations are discussed below.

The straightening of aircraft trajectories changes the dynamics of the air traffic situation with important consequences for controller cognitive complexity. Straighter trajectories have fewer trajectory change points and support simpler standard flow abstractions. They are easier to project as fewer degrees-of-freedom are required to account for the timing of trajectory changes. Monitoring is easier as there are fewer opportunities for navigation errors and divergences from the underlying route structure are more salient. Optimizing the route structure consistent with these simplification mechanisms provides opportunities to reduce cognitive complexity.

A second impact, however, is the potential for changes to the dynamics of the situation to undermine the bases for controller abstractions. Preserving the structural bases enables continued use of those abstractions in controller working mental models, reducing cognitive complexity. The bases of standard flow abstractions are preserved by route structures that segregate traffic, standardize commands, minimize intra-flow interactions, and pre-solve tasks. A key cognitive complexity consideration is avoiding creating routes that undermine these properties. For example, developing route structures that mix aircraft with different dynamics will create intra-flow interactions, undermining the usefulness of a standard flow abstraction in the controller's working mental model.

Preserving the structural basis also applies to grouping abstractions. New route structures that take advantage of new RNP capabilities to define vertical paths change the dynamics of the situation in ways that can affect a controller's grouping abstractions. Aircraft climbing or descending undermine the independence between discrete altitude levels that forms the basis for abstractions decomposing the situation by altitude. Minimizing the time aircraft spend climbing or descending mitigates this effect.

A third and final example is the potential for optimized route structures to increase the number of critical points. Realigning routes will shift the locations of flow crossings and merge points, potentially increasing the number of critical points. For example, in Figure 8–4, straightening airway V5 to provide a more efficient routing around the Buckeye SUA creates multiple additional critical points (circles) at new crossings with existing airways (e.g. V128, V97, V517).

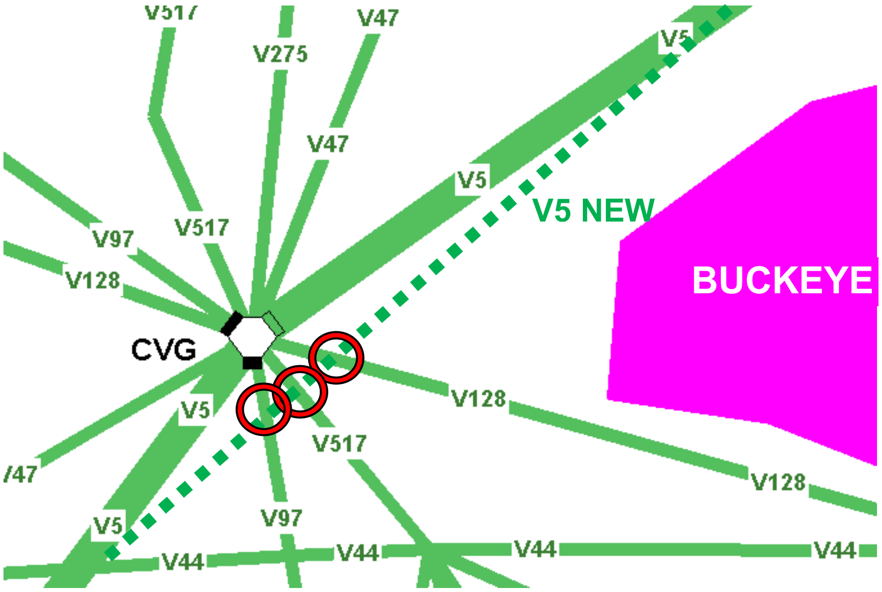

Figure 8–4. New critical points (circles) created by straightening of airway V5.

Increasing the number of critical points in a sector affects cognitive complexity in several ways. Distributing events, such as merges, conflicts, and trajectory changes, over multiple critical points increases the potential for simultaneous events. Simultaneous events, a key complexity factor, create the need for working mental models capable of supporting parallel evaluation and planning processes associated with the multiple events. Increases in the number of critical points can also increase cognitive complexity by leading to inter-dependent critical points. Inter-dependent critical points are cases where there is insufficient time or airspace available for a controller to independently control an aircraft's time-of-arrival at the distinct critical points. Evaluations and planning decisions at inter-dependent critical points become linked, making critical point abstractions less effective at reducing the order of the working mental model. Minimizing the number of critical points an individual aircraft passes through and maximizing the space between critical points are two means of reducing the dependencies between critical points.

The importance of limiting the number of critical points in a sector is consistent with current practices and experimental results. An analysis of traffic density through the 46 sectors in Washington Center showed an average of two crossing and/or merge points per sector. A part-task experiment showed merging operations were significantly simpler when concentrated at a single merge point rather than spread amongst multiple merge points (Histon *et al.* 2002).

The impacts of changes to the dynamics on cognitive complexity are not always straightforward. While limiting the number of critical points is a key consideration, there are cognitive complexity advantages to dispersing traffic through multiple critical points. Consolidating traffic that would not otherwise conflict at a critical point creates tasks associated with detecting and resolving conflicts and unnecessarily limits capacity. Using two independent critical points for such traffic increases the number of critical points but would decrease cognitive complexity as the segregation of traffic pre-solves the tasks associated with detecting and resolving conflicts.

8.2.3 Summary and Further Opportunities to Increase Efficiency

Opportunities to increase the efficiency of the route structure require careful consideration of the balance between efficiency gains and potential increases to a controller's cognitive complexity. Simple trajectories avoid monitoring and projection challenges but must be balanced against potential increases in the number of critical points. Key cognitive complexity challenges include the need to preserve the bases of standard flow and critical point abstractions and the need to limit the number of critical points.

Even greater improvements in efficiency are possible by adjusting route structures to adapt to dynamic environmental conditions such as changes in the wind. Routes favorably aligned with the wind provide significant fuel and time savings, either through the benefits of a tail wind or the avoidance of a head wind. However, constant modifications of underlying route structures will likely challenge a controller's ability to develop and apply standard flow abstractions. Flow patterns that are novel and unique each day would not support the full simplification benefits available from standard flow abstractions including the incorporation of standard commands and known relationships with other parts of the airspace. Shifts amongst a set of discrete "plays," or pre-evaluated route structures each aligned to general wind patterns, may be a feasible compromise between supporting simplifying abstractions and increasing efficiency.

8.3 Opportunity II: Increasing Capacity

Limited capacity is a second performance shortfall of the current system. Many existing route structures are incapable of providing sufficient capacity to meet demand, leading to delays. This is exacerbated when convective weather shuts down routes, concentrating demand on the remaining routes. Particularly in high traffic density regions, existing route structures are already tightly packed, limiting the potential to add capacity by adding routes. However, there is an opportunity to add additional capacity within the confines of the existing route structure. Multi-laning, or adding multiple parallel routes to existing routes, is one opportunity to create additional capacity in the system. If done in ways consistent with controller structure-based abstractions, the cognitive complexity benefits should delay the onset of congestion mode operations (Figure 8–5).

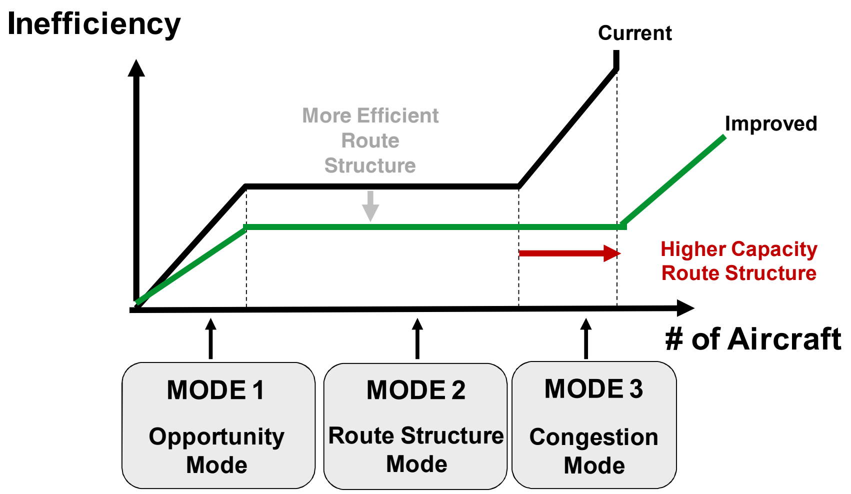

Figure 8–5. Improving capacity of the route structure.

8.3.1 Multi-laning Existing Route structures

The increased precision of aircraft trajectories in RNAV and RNP operations provides opportunities to "multi-lane" existing flows through the addition of minimally spaced, laterally separated, routes. As illustrated in Figure 8–6, additional routes can be added parallel to existing jet route definitions. Combined with reductions in separation standards, parallel lanes can be deployed within the confines of the existing route structure.

The existing route structure supports both uni-directional and bi-directional standard flows; multi-laning could be considered for either type of route. However, in order to simplify and narrow the scope of the analysis, the discussion below is limited to opportunities to multi-lane existing uni-directional routes.

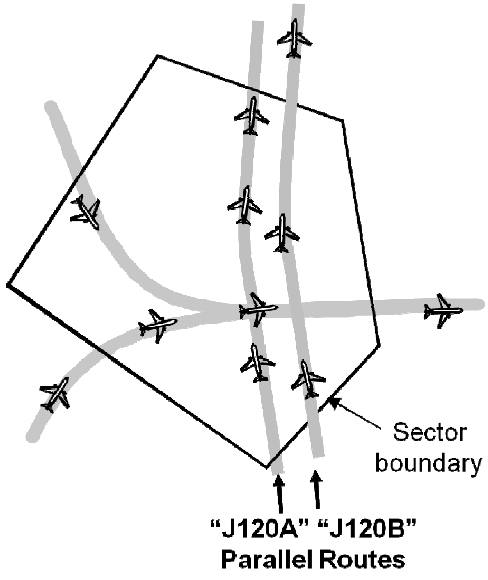

Figure 8–6. Multi-laning by adding closely spaced parallel jet routes.

8.3.2 Cognitive Complexity Considerations of Multi-laning

New elements of framework and pattern structure are created by multi-laning. The parallel routes and flows add structure that will appear very similar to existing structure and may therefore be thought to have little impact on cognitive complexity. However, adding the new elements will change how new and existing flows and routes interact.

In the context of the cognitive process model, the primary effects of multi-laning are on the dynamics of the air traffic situation and the commands available to the controller. Both have important consequences for controller structure-based abstractions and controller cognitive complexity.

Considerations from Impact on Dynamics and Abstractions

Two examples are presented below illustrating the impact of changes to the dynamics on controller abstractions and related cognitive complexity considerations.

Implementing multi-laning in a manner that makes the dynamics of the situation consistent with existing abstractions offers considerable cognitive complexity advantages. A parallel and consistent route structure creates similar dynamics across the lanes, providing a basis for a generalized standard flow abstraction of the collection of lanes. A generalized standard flow abstraction simplifies and reduces the order of working mental models used to evaluate and project relationships between the generalized flow and other parts of the situation. Implementing multi-laning in ways that eliminate the need for a controller to track lane membership would enable such generalized abstractions. For example, having a common procedure for all lanes reduces the need to track lane membership when planning the situation.

Standardizing the dynamics within each lane minimizes the potential for intra-lane interactions and makes the individual lanes consistent with existing standard flow abstractions. Establishing separate lanes based on the performance capabilities of aircraft helps reduce intra-lane interactions and supports controller use of performance-based grouping abstractions. For example, “slow” and “fast” lanes reduce the mixing of aircraft speeds, standardizing the relative dynamics of aircraft within each lane.

A second example is the consequences of the changes to the dynamics at critical points. Multi-laning can lead to significant increases in the number of critical points. This occurs if controllers treat the crossing points formed by individual lanes and crossing traffic as individual critical points. The number of critical points at a crossing of two multiple lane flows scales with the product of the number of lanes in each flow. The close proximity of the critical points also creates critical points that are inter-dependent. The inter-dependency and increase in number of critical points create a need for higher order working mental models and the cognitive complexity consequences discussed in Opportunity I above.

Alternatively, controllers might retain a single 'master' critical point at the generalized point of intersection of the multiple lanes. This also raises cognitive complexity challenges as it significantly increases the number of aircraft associated with the critical point, increasing the cognitive complexity of projecting. Additional degrees-of-freedom are required in the working mental model in order to track the flow and lane membership of an aircraft. This is necessary to discriminate between 'ties' between aircraft from different flows and 'ties' between aircraft from different lanes in the same flow.

Multi-lane route structures also increase the number of sources of aircraft at merge points. If there are multiple lane outputs from the merge point, controllers must manage lane assignments and the potential for lane changes. Both effects increase the degrees-of-freedom at the merge point and create a need for more cognitively complex working mental models.

Considerations from Impact on Commands

Additional cognitive complexity considerations can be identified by considering the impact of multi-laning on the commands used to intervene in the situation.

The new multi-lane route structure helps reduce cognitive complexity by providing structural support for simpler resolution maneuvers. The presence of one or more parallel lanes gives the controller a bounded, pre-evaluated, standardized resolution maneuver, simplifying the working mental model used to evaluate and plan the resolution maneuver. This simplifies management of intra-flow interactions between aircraft as an aircraft overtaking another can be commanded to sidestep to a parallel lane. In contrast, resolution maneuvers using vectors create unbounded trajectories and require evaluating and timing multiple interventions. Monitoring conformance during vector maneuvers is more difficult as there is no obvious structural basis for comparison.

Multi-laning also has the potential to negatively affect cognitive complexity by limiting the airspace available for resolutions and potential for standardized resolution maneuvers. Limited airspace being available for resolution maneuvers was identified in the field observations as a key complexity factor (Chapter 4). In current "single lane" operations, airspace is typically available on at least one side of the track for resolution maneuvers.[36] The left image in Figure 8–7 illustrates an example of the use of maneuvering airspace in current operations to establish in-trail separation between aircraft in a flow at sector boundaries. As shown in the right image in Figure

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[36] This is in addition to the potential for vertical resolution actions.

8–7, in multi-lane route structures, the additional lanes can block access to the airspace used for maneuvers, limiting the types of resolution commands a controller could use. With three or more lanes, at least one lane will be "boxed in," restricting standardized resolution maneuvers to only altitude changes. In addition, the higher density of traffic will create a wider range of traffic configurations. This hampers the use of standard commands, reducing the effectiveness of a controller's standard flow abstractions.

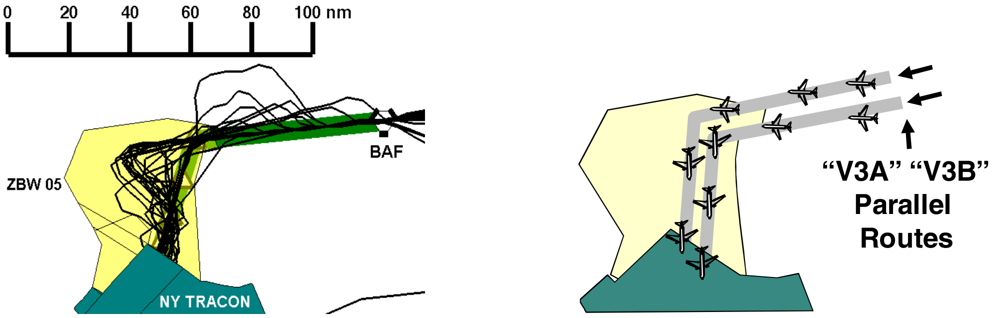

Figure 8–7. **(Left) Examples of maneuvers (thin lines) to meet entry and exit constraints for traffic destined New York (NY) TRACON through Boston Center sector 05 (ZBW 05 - yellow). (Right) Multi-lane routes block access to maneuvering airspace and create challenges for establishing standardized resolution maneuvers.**

Additional Challenges

The discussion above highlights only some of the cognitive complexity challenges raised by introducing multi-lane route structures. Using reduced separation standards between the lanes requires additional degrees-of-freedom to track the multiple separation standards, creating more complex working mental models. Other challenges include establishing aircraft on the multiple parallel routes, removing aircraft from the routes, and the operation of closely spaced parallel routes in the presence of deviations and disrupted operations. Additional aircraft will also increase the density of information on the controller's display, adding to the challenge of screen clutter. The close proximity of aircraft on the multiple lanes means supporting effective data tag management and developing means of minimizing the amount of information displayed will become increasingly important.

8.3.3 Summary and Opportunities to Mitigate Cognitive Complexity Challenges

Examining the impact of multi-laning on controller use of structure and structure-based abstractions identifies several significant cognitive complexity considerations. Multi-laning has the potential to significantly increase the order of the problem, increasing cognitive complexity. Crossing and merge points become more challenging with higher order interactions. The additional lanes provide simpler commands, but also block access to airspace used for maneuvers. The increased density of aircraft may hamper the use of standard commands, reducing the effectiveness of a controller's standard flow abstractions.

Structure supporting grouping and responsibility abstractions can help mitigate some of the cognitive complexity challenges described above. Grouping and responsibility abstractions can be supported by introducing new procedures and operational concepts that remove responsibility for the relationships between aircraft within the multi-lane route structure from the controller.

Expanded use of procedures delegating separation responsibility to pilots on the multiple lanes can take advantage of controller use of responsibility abstractions. Limited self-separation between aircraft within the multi-lane flow would allow controllers to abstract away the interactions between the flows. This frees cognitive resources as fewer degrees-of-freedom would be needed in their working mental model. In turn, this allows controllers to focus more on managing interactions between the multi-lanes and crossing or nonstandard traffic.

Delegating self-separation and new procedures could also be used to create platoons of aircraft supporting grouping abstractions. Aircraft organized into a platoon would be delegated responsibility for their internal separation. This would allow a controller to abstract the group into a single entity, enabling the controller to consider the multiple lanes as a single track flow. Changes to displays reinforcing the grouped nature of the platoon would encourage use of such abstractions. The formation and break up of such groups as well as contingencies for on-board equipment failures and emergencies are additional cognitive complexity challenges.

8.4 Opportunity III: Increasing Robustness

Robustness in the face of disrupted operations is another significant challenge for the performance of the ATC system. Many factors can disrupt operations including convective weather, emergencies, and/or events outside of a sector such as snow clearing operations at an airport. Disruptions lead to aircraft holding and deviating from standard routes through the sector, two key complexity factors identified in Chapter 4. During disrupted operations, the communication and implementation of commands can be challenging as the framework structure (e.g. waypoints, path definitions or other reference elements) may not be available or in useful places for implementing trajectory changes.

Disruptions create unique and novel dynamics that create uncertainty in an aircraft's trajectory and dynamics. Deviations create uncertainty in the aircraft trajectory as the time, location, and path used to return to the flight planned course are undetermined. The trajectories of deviating aircraft are unique and without fixed, pre-evaluated, relationships to other elements of the airspace such as other traffic flows, Special Use Airspace (SUA) and/or terrain. This undermines the controller's ability to use existing structure-based abstractions to develop simple, effective working mental models appropriate for modeling the dynamics of the situation. The lack of common spatial locations undermines a controller's existing critical point abstractions. In disrupted operations controllers must maintain higher order working mental models that integrate multiple space and time dimensions when evaluating relationships between aircraft. Designing the airspace structure such that existing abstractions can "bend without breaking" would allow their use over a wider range of operating conditions and lead to operations that are more robust to disruptions.

8.4.1 Opportunities to Support More Robust Abstractions

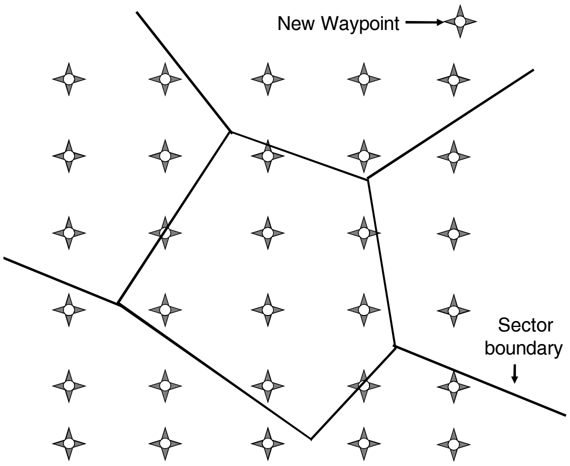

Figure 8–8. Increased density of waypoints.

There are several opportunities to improve the structure of the system in order to promote continued use of standard flow abstractions during disrupted operations. Increasing the density of waypoints, as contemplated by the introduction of the Navigational Reference System (NRS), is one opportunity. Initial deployment of the NRS has added RNAV waypoints at every other degree of longitude and every thirty minutes of latitude (Mikolay, 2003).[37] Figure 8–8 illustrates a notional sector with a grid of additional waypoints. Providing additional waypoints provides controllers with the means to impose structure on deviating aircraft. A series of aircraft deviating around a common obstacle can each be cleared to fly directly to a common waypoint, retaining the arrangement of aircraft into a standard flow (Figure 8–9). Increasing the density of waypoints increases the probability of a waypoint being in an appropriate and useful location, e.g. 'in the right place.'

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[37] This is approximately 30 miles by 60 miles.

As a key element in the framework layer, increasing the number of waypoints adds flexibility to the design of higher layers of structure including the development of more sophisticated procedures and more complicated trajectories. An important opportunity enabled by the increased density is the deployment of pre-evaluated alternative airways and jet routes.[38] Alternative airways and jet routes (i.e. alternative route structures) provide more flexible and robust operations near convective weather or other disruptions that make standard routes unusable. Alternative routes can be adapted and pre-evaluated for separation from other flows, Special Use Airspace (SUA), terrain and other factors. Pre-evaluated route structures remove coordination requirements at sector boundaries. The alternative route can span multiple sectors and can be designed to accommodate the specific traffic requirements in each sector. As well, alternative procedures governing traffic at sector interfaces can be developed.

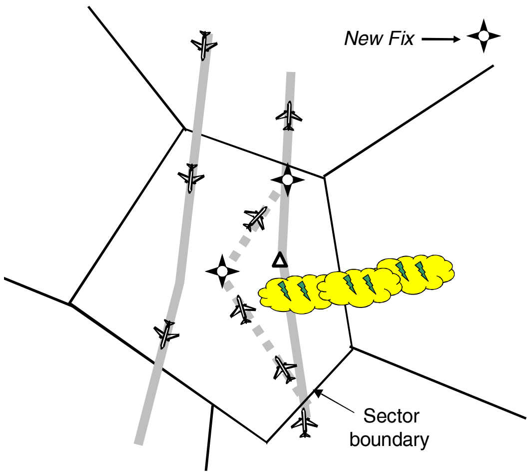

Figure 8–9. **Clearing aircraft direct to common waypoint retains relative arrangement of aircraft.**

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[38] This opportunity is similar, but on a smaller, sector specific, scale to current “Playbook” routings used for traffic flow management.

A simple example consisting of an alternative jet route offset from an existing jet route is illustrated in Figure 8–10. The dashed line in Figure 8–10 denotes jet route "J547A", a pre-defined and pre-evaluated alternative basis for the flow structure. The example in Figure 8–10 is one of many possible path definitions that can be introduced to provide alternative route structures more robust to disruptions.

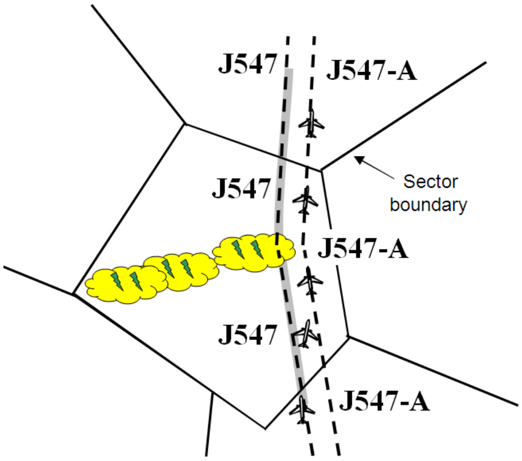

Figure 8–10. **Pre-defined and evaluated alternative framework elements can provide support for continued standard flow operations in presence of convective weather.**

8.4.2 Cognitive Complexity Considerations of Alternative Structures

Increasing the density of waypoints and introducing alternative route structures change the framework layer in the structure hierarchy. The changes create opportunities for controllers to modify existing patterns, impose new patterns or transition to known alternative patterns. By examining how these changes in the structure affect the dynamics, the task, and the commands available, key cognitive complexity considerations can be identified.

Considerations from Impact on Dynamics and Abstractions

Examples of cognitive complexity considerations arising from the impact of these structural changes on the dynamics of the situation, including related impacts on controller abstractions, are presented below.

Deploying additional waypoints and pre-evaluated alternative route structures helps standardize the dynamics that occur during disrupted operations. This facilitates continued use of standard flow abstractions as existing ones can "bend without breaking" and helps provide a basis for new, improvised, standard flow abstractions. Clearing aircraft to fly direct to a waypoint produces greater consistency in aircraft trajectories and reduces ambiguity about where an aircraft will turn back on course. This increases predictability and places a bound on the magnitude of an aircraft's deviation. Bounding the deviation limits the degrees-of-freedom in the working mental model, decreasing cognitive complexity and making it easier to evaluate how the deviating aircraft interacts with other traffic flows and airspace elements. Repeated use of the same or similar "direct to" clearance will retain the relative arrangement of aircraft in an existing flow, supporting extended use of a controller's standard flow abstraction.

The introduction of alternative references also helps support continued use of critical point abstractions and hence can help reduce cognitive complexity. Using the increased density of waypoints to bound the deviations for all aircraft in a flow supports development and use of ad hoc critical point abstractions. Aircraft trajectory change points occur at a common location, simplifying conformance monitoring. Maintaining a common path for deviating aircraft creates repeated, consistent, interactions with other aircraft and airspace elements. Pre-defined route structures maintain the general use of standard flows and hence will tend to promote concentrations of traffic, consistent with critical point abstractions.

However, introducing alternative structure's also multiplies the set of potential patterns and dynamics in the sector, creating challenges for controller abstractions. Multiple sets of abstractions must be learned and managed with each set applicable under different conditions. Maintaining multiple standard flow and critical point abstractions, each specific to an alternative route structure, could lead to confusion and inappropriate application. In addition, alternative route structures spanning multiple sectors require careful coordination to maintain the integrity of aircraft clearances across the sectors. Transitions between using existing and alternative route structures must be carefully managed to ensure controller's expectations and abstractions are consistent with aircraft dynamics.

Considerations from Impact on Task and Commands

Examining the impact of introducing alternative structures on the controller's task and commands available to intervene in the situation can be used to identify additional cognitive complexity considerations. The three examples below illustrate the cognitive complexity advantages and challenges that can emerge.

Alternative route structures can help reduce cognitive complexity by simplifying the types of evaluations that controllers have to perform in real-time. Pre-defined alternative route structures remove the need to evaluate the consequences of moving a flow on its relationship with other flows and acceptability at interfaces with surrounding airspace. Performing such evaluations in real-time is cognitively challenging, requiring complicated mental models and time-consuming coordination and communication with surrounding controllers. Alternative route structures offload these evaluations from the controller and hence help reduce cognitive complexity.

A second example is the shift in tasks between pilots and controllers that can result from introducing new waypoints and alternative route structures. In current operations, the pilot typically has the task of checking that the deviated trajectory is sufficient to clear the weather and determining when the aircraft can return to the flight planned route. In the proposed opportunities, the controller gains the task of determining a waypoint or alternative route structure that remains clear of the weather. Higher order working mental models, with more detailed representations of the dynamics and intensity of the disruptive weather, are required, increasing cognitive complexity. Advances in weather surveillance and prediction could be incorporated into new display tools that suggest appropriate waypoints along a proposed deviating course. This would transfer parts of the new task from the controller to automation, helping to mitigate this issue. In addition, the ability of pilots to propose deviations in terms of the new waypoints or alternative route structures offsets some of the transfer of the task to the controller.

A third example is the impact that expanding the number of waypoints has on controller-pilot communications. To be used in commands, each waypoint must have a unique identifier that is easily communicated. The existing naming convention does not scale to the density required and hence a new naming convention is necessary. The NRS system has developed a shorthand naming convention that provides a unique five letter code to each waypoint. Initial usability evaluations showed controllers found the waypoints useful, but the naming convention could be unwieldy in verbal communications and presented challenges with data entry (Mills *et al.*, 2004). The implementation of new datalink communication protocols may alleviate some of these concerns.

8.4.3 Summary and Further Opportunities to Increase Robustness

Supporting continued use of existing structure-based abstractions, e.g. allowing them to "bend without breaking," is an important cognitive complexity advantage of introducing alternative structures. However, alternative structures require controllers to develop and maintain multiple sets of abstractions. This creates training challenges and could create confusion and inappropriate application. Alternative structures that are pre-evaluated provide a solid base for simplifying abstractions. The new structure can also help simplify commands though new naming conventions may pose implementation challenges.

Further Opportunity: Dynamic Alternative Structures. Pre-defined fixed offsets from existing airways may not provide sufficient flexibility; alternative approaches such as allowing controllers to dynamically set an offset distance, e.g. "J547A is 5 miles south today" may provide more flexible and usable arrangements. New operations concepts may enable the implementation of real-time adjustments to airway and/or jet route definitions. Tools can be provided to controllers allowing them to adjust existing waypoints on a route to stretch the flow around an obstacle or weather formation (Figure 8–11).

Automation and new display tools capable of real-time evaluation of the consequences of moving a flow will likely be key to sustaining standard flow abstractions in such an environment. Such automated evaluation may be sufficient to sustain standard flow abstractions and offset the lack of fixed relationships between the aircraft in the flow and other parts of the situation. Initialization and termination of the use of dynamic offsets will likely increase coordination between controllers, contributing to an increase in cognitive complexity.

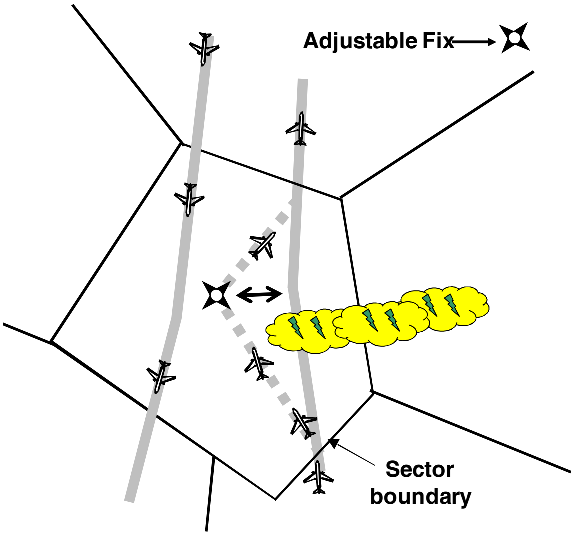

Figure 8–11. **New operations concepts and decision support tools may enable real-time adjustment of standard flows.**

8.5 Opportunity IV: New Operational Concepts

The performance challenges described above are motivating new operational concepts (Con-Ops). New technologies and Con-Ops will change the role and tasks of controllers but cognitive complexity is expected to continue to be a limiting factor on performance capabilities of the next generation of ATC systems. In evaluating the feasibility of new Con-Ops, it is important to consider how the Con-Ops would change the structure of the system and its related impacts on controller cognitive complexity. This section discusses one commonly proposed component of the next generation of ATC systems, 4-dimensional trajectories (4DTs).

8.5.1 4 Dimensional Trajectories

The shift to a 4D trajectory based system is anticipated to be a key aspect of next generation ATC systems. 4DTs add an additional dimension, time, to an aircraft's clearance. A simple example of a 4DT is shown in Figure 8–12; aircraft A is shown with a clearance to fly to the fixes WAYPT and PLACE, with a requirement to be over the point WAYPT at a specific time (12:05). 4DTs include controlled time-of-arrivals (CTAs) to one or more locations in an aircraft's clearance. Through careful scheduling of the CTAs, conflicts between aircraft or between aircraft and procedures can be resolved.

Many variants of 4DTs are under consideration in the proposals for next generation ATC systems. Important issues such as the number of CTAs defining a 4DT, the actions an aircraft can take to meet a CTA, and what mechanisms controllers will use to update and control CTAs and 4DTs remain in flux. However, the core concept of defining and requiring aircraft to meet controlled time-of-arrivals at particular points in space is well-established.

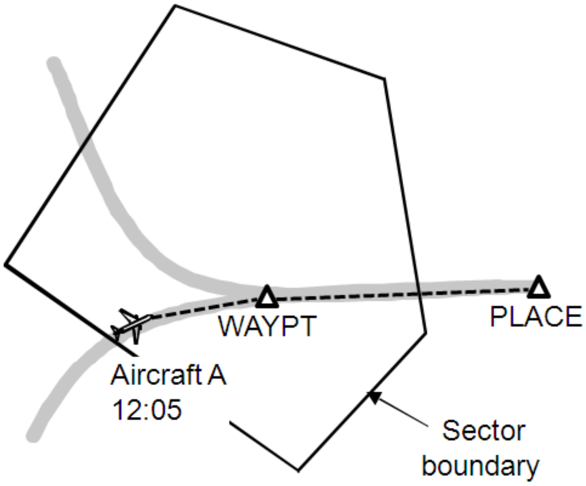

Figure 8–12. **4D trajectory with a controlled time-of-arrival at WAYPT.**

8.5.2 Cognitive Complexity Considerations of 4 Dimensional Trajectories

4DT operations will introduce significant changes at all layers of the structure hierarchy. The framework layer structure of routes will likely be relaxed, new ATC and published operating procedures introduced, and new patterns formed. The cognitive process model is a useful tool for identifying consequences of these changes in the structure for controller cognitive complexity. Key cognitive complexity considerations were identified by examining how these changes in the structure might affect controller abstractions, the task, the dynamics, and the commands available.

Considerations from Impact on Abstractions

The changes to structure associated with the introduction of 4DTs will have significant impact on a controller's abstractions. Two examples illustrate the kinds of cognitive complexity considerations that emerge from the impact of 4DTs on controller abstractions.

The introduction of 4DTs will likely prompt significant changes to the structure supporting current abstractions used by controllers. Relaxation of spatial constraints on aircraft trajectories removes the structural bases for current standard flow abstractions. This also affects some controller critical point abstractions as traffic no longer necessarily crosses and merges at common standardized locations. In isolation, these effects suggest 4DTs could substantially increase cognitive complexity.

However, a second example of cognitive complexity considerations is the potential for 4DT operations to create opportunities for new forms of abstractions. 4DT operations will likely change how controllers incorporate time in their working mental models. Time-based decision-support tools, such as the time-line shown in Figure 8–13, help support new temporal abstractions based on CTA points. Abstractions based on CTA points are natural extensions of existing critical point abstractions to include an assigned time. Similar mechanisms to those of critical points can be expected; for example, abstractions based on CTA points support decomposition of the task based on the time-of-arrival at the CTA. CTAs also provide a distinct basis for monitoring conformance of aircraft to their 4DT clearance.

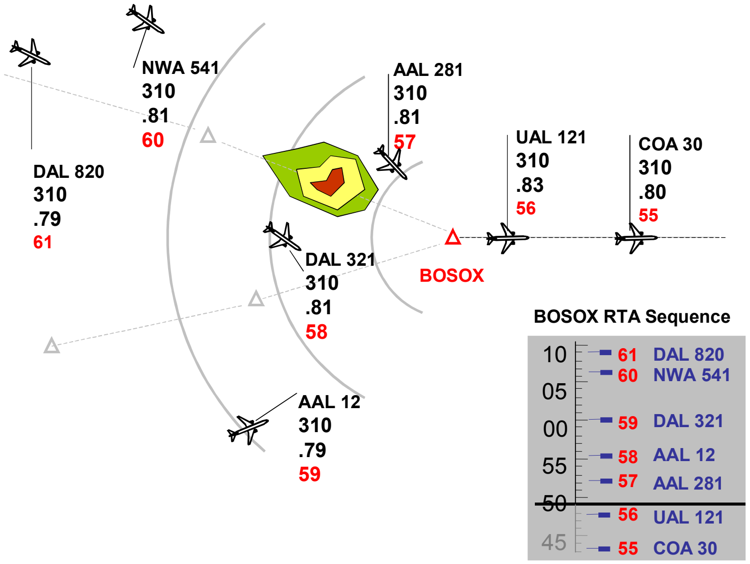

Figure 8–13. Example of a possible basis for time-based abstraction in a 4D trajectory environment.

The similarities between CTAs and traditional critical points suggest many of the same cognitive complexity considerations described in Opportunity I and II will apply to the new abstractions. A key condition for the effectiveness of abstractions based on CTAs is that the CTAs for different aircraft share a common spatial location. Sharing a common location reduces the degrees-of-freedom in the working mental model and allows direct comparison between the assigned times. In contrast, two non co-located CTA points do not offer any direct reductions in the degrees-of-freedom in the working mental model, a comparative increase in cognitive complexity. Similar to critical points, too many CTA points has the potential to overwhelm controllers. Aircraft that pass through multiple CTAs can create inter-dependent CTAs, where changes at one CTA will impact the feasibility of meeting other CTAs. Such linked problems substantially increase the degrees-of-freedom required in the working mental model, potentially making the situation cognitively intractable to the controller. Limiting the number of CTAs per aircraft decreases the potential for inter-dependent CTA points, reducing cognitive complexity.

Considerations from Impact on Dynamics

Cognitive complexity considerations can also be identified by examining the impact of 4DTs on the dynamics of the air traffic situation. Three examples illustrate cognitive complexity considerations that will need to be accounted for.

Aircraft maneuvering to conform to CTAs, or meet revised CTAs, fundamentally changes the dynamics of the situation by introducing uncontrolled and autonomous aircraft behaviors. Aircraft must be delegated one or more degrees-of-freedom and be able to autonomously use one or more of speed changes, lateral maneuvers, and/or vertical maneuvers to adjust their trajectory in order to meet the assigned CTA.[39] The choice and magnitude of maneuvers will depend on many factors including the time delay needing to be absorbed / gained, how far the aircraft is from the CTA point, and which degrees-of-freedom are delegated to the pilot. This introduces uncertainty into the dynamics as there are many different trajectories that are in conformance with the assigned CTA.

For the controller, uncertainty in the dynamics makes it more difficult to accurately project the situation and use simplifying abstractions. Evaluating the feasibility of proposed changes to CTAs is more difficult if a controller is uncertain of how the dynamics of other aircraft might impact the capability of an aircraft to meet the assigned CTA. There are multiple different trajectories, each with unique dynamics, that are compatible with an assigned time-of-arrival, making it more challenging to monitor conformance to the CTAs. Delegating the freedom to maneuver also includes the timing of those maneuvers, further adding to the variability,

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[39] Wind varies in speed and direction with altitude providing an additional means of adjusting an aircraft's ground speed in order to meet the CTA.

undermining the predictability of the situation, and creating additional cognitive complexity challenges.

The effects on cognitive complexity of the variability in dynamics in 4DT operations can be mitigated in part by considering means of standardizing aircraft maneuvers to meet a CTA. Restricting aircraft to maneuvering in a single degree of freedom (e.g. speed-only, or laterally only) also simplifies the dynamics for the controller.

A second example of considerations arising from changes to the dynamics is the impact on existing structure-based strategies. The granting of freedom to maneuver to meet a CTA will undermine existing strategies used to impose structure in order to simplify working mental models. For example, in current operations controllers can impose the same speed on all aircraft in the situation, simplifying projecting by allowing a controller to use a constant speed grouping abstraction (Davison-Reynolds, 2006). Delegating to aircraft a degree-of-freedom for maneuvering interferes with a controller's ability to impose a structure and standardize the dynamics of aircraft in the situation.

A third example of the consequences of the impact on dynamics is the potential for controllers to be responsible for a mix of aircraft dynamics. Airspace with both aircraft cleared on 4DTs and aircraft receiving traditional clearances creates a mix of the types of aircraft dynamics and tasks for the controller. This creates a "mixed equipage" problem (Pina, 2006). Situations mixing aircraft with different dynamics or navigation, communication, or surveillance capabilities require working mental models with more degrees-of-freedom. Controllers must individually track and assess each aircraft's capabilities, adding additional tasks and dimensions to their working mental model of the situation.

These challenges can be mitigated by introducing structure consistent with controller use of grouping abstractions to decompose a situation. Procedural changes that segregate aircraft by capability and/or equipage level, such as distinct altitudes for aircraft capable of 4DT operations, simplifies judgments as to what dynamics can be expected of aircraft and what control can be asserted. This reduces the degrees-of-freedom in a controller's working mental model.

Considerations from Impact on Tasks

Cognitive complexity considerations can also be identified by examining how 4DTs will likely modify the controller's task.

Managing CTAs changes the task in ways that could require more sophisticated working mental models and hence have the potential to increase cognitive complexity. In 4DT operations, time is an explicitly controlled parameter and task requirement. CTAs add a new states to be monitored (CTA times) and the effects of CTA times on aircraft dynamics must be accounted for in projections. These affects have the potential to increase cognitive complexity.

However, these potential increases must be balanced against the potential for 4DTs to reduce cognitive complexity by offloading parts of the task from the controller. In 4DT operations, planning the changes to aircraft trajectories required to meet assigned CTAs becomes the responsibility of the pilot/aircraft. In addition, if the CTAs are stable, and assigned sufficiently early, the separation between aircraft is fixed at the CTA point, pre-solving controller tasks of conflict management and compliance with traffic flow management initiatives. This allows controllers to use simpler working mental models and thus reduces cognitive complexity.

Impact on Commands

Additional cognitive complexity considerations, and possible mitigating factors, can be identified by examining how 4DTs impact controller commands.

4DT operations are expected to prompt a transition to time-based control mechanisms with significant cognitive complexity advantages. Specifying a time-of-arrival at a common spatial location allows controllers to resolve issues with a single command. As long as aircraft conform to the CTAs, the assigned CTAs are guaranteed to resolve the interaction at the common spatial location. This allows controllers to transform the task from more cognitively complex decision processes of evaluation (requiring higher order working mental models spanning multiple aircraft) to simpler monitoring decision processes (requiring lower order working mental models focused on one aircraft).[40] In contrast, resolutions using vectors require periodic re-evaluation to check that stochastic effects such as variations in the wind have not eroded the planned separation.

Examining the impact of 4DTs on commands suggest there is an opportunity to introduce new forms of spatial commands to mitigate the cognitive complexity considerations arising from the delegation of at least one degree-of-freedom for maneuvering discussed above. New spatial command mechanisms would provide controllers ways of regulating and managing the

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[40] This is a similar effect to using altitude changes as resolution actions. A single command resolves the original conflict immediately and, subject to aircraft maintaining their assigned altitudes, the solution is guaranteed.

uncertainty in dynamics created by freely maneuvering aircraft. Bounds on acceptable maneuvers as well as means of preventing certain maneuvers will likely require expansion of controller-pilot commands and phraseology. As a simple example, if aircraft are given freedom to laterally maneuver to meet their CTA, a controller may want to impose a restriction on which side of the aircraft's track the lateral maneuver occurs.

8.5.3 Summary of Opportunity

Introducing 4DTs will bring many significant changes to the structure of the system. Examining how these changes affect key influences of structure in the context of the cognitive process model is a useful means of identifying potential cognitive complexity advantages and challenges.

Examples of cognitive complexity advantages of 4DTs include support for new temporal abstractions, the offloading of tasks from the controller, and new command mechanisms that support immediate problem resolution. However, 4DTs also create challenges. 4DTs increase the required order of a controller's working mental model by adding time as an additional state affecting projection and monitoring. The delegation of authority to maneuver in at least one degree-of-freedom to meet CTAs creates uncertainty in aircraft dynamics creating challenges for projection, monitoring and evaluating.

8.6 Chapter Summary

This chapter has examined four opportunities to increase the capacity, efficiency, and robustness of current and future ATC systems. The consequences of the changes to structure resulting from each opportunity were used to identify examples of key cognitive complexity considerations. Taking these considerations into account when developing opportunities to increase the performance of the system allows system designers to manipulate structure in ways that reduce cognitive complexity. This helps manage the risk of cognitive complexity considerations limiting the feasibility of the opportunity.

Key considerations included the importance of accounting for potential impacts on controller abstractions. Preserving the bases of existing abstractions enables continued use of structure-based abstractions as cognitive complexity reduction mechanisms. Helping existing abstractions "bend without breaking" supports their use and cognitive complexity benefits over a wide range of conditions.

A recurring and common consideration is minimizing the order of the problem, or degrees-of-freedom required in a working mental model. Simplifying trajectories, by straightening routes and reducing the number of trajectory change points, as well as standardizing dynamics are two ways of reducing the degrees-of-freedom in controller working mental models. Supporting the formation of platoons provides a basis for grouping abstractions that allow the controller to abstract multiple aircraft into a single entity, reducing the order of the problem for the controller. Limiting the number of critical points or CTA points aircraft pass through limits the potential for linked and inter-dependent problems that require higher order working mental models.

The analyses also highlighted the importance of considering the impact of changes to commands. Commands that immediately and unequivocally resolve problems shift decisions from more complex evaluating to simpler conformance monitoring. Pre-evaluated command mechanisms, such as fixed offset route structures, simplify planning. Preserving airspace for maneuvering supports standard commands which also simplifies planning.

In addition to evaluating opportunities to improve the system, the cognitive process model and structure-based abstractions are useful tools for identifying opportunities to improve the controller training process. This is discussed in the following chapter.

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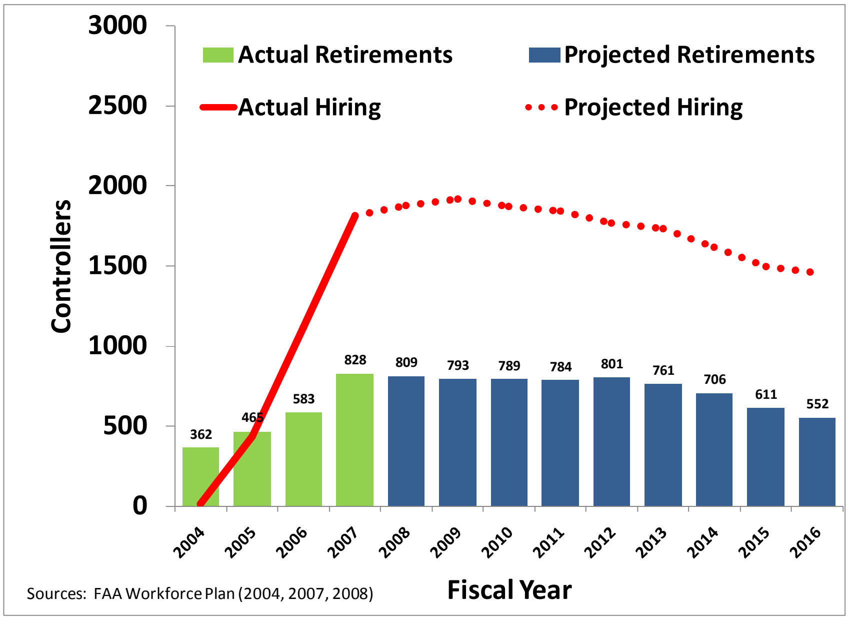
CHAPTER 9 Implications of Structure-Based Abstractions for Improving Controller Training

This chapter presents a second application of the cognitive process model and structure-based abstractions and demonstrates their utility in identifying opportunities to improve the controller training process. The cognitive process model is used as the basis for a cognitive review of the current en route controller training process. The review identified several promising opportunities to change either the training process and/or operational practices in order to increase staffing flexibility, reduce training times, lower training costs, and/or more effectively utilize training resources.

9.1 The Need for Improvements to Controller Training and Increased Staffing Flexibility

The FAA has been experiencing substantial increases in the number of controllers retiring; the large number of retirements is projected to continue for at least a decade (Figure 9—1). Controllers hired as replacements for the 11,350 controllers fired during the Professional Air Traffic Controllers Organization (PATCO) strike in 1981 are rapidly reaching retirement eligibility and leaving the FAA (General Accounting Office, 2002). Controllers are also being promoted to replace supervisors who are also rapidly retiring (General Accounting Office, 2002). In response, controller hiring has been accelerated and is projected to remain at elevated levels for the next decade.

On average, it takes between 3 and 5 years to complete all requirements necessary to become a certified professional controller (FAA, 2005a). New controllers require extensive training; there are no existing pools of qualified controllers that can be quickly tapped to replace retiring controllers. Due to the long training times, significant investment in the form of facilities, instructors, and trainee pay is made on each developmental. The lengthy training time create significant costs and could lead to a shortfall in certified controllers with significant consequences on operations of the National Airspace System including reductions in aircraft flow rates (General Accounting Office, 2002).



Sources: FAA Workforce Plan (2004, 2007, 2008)

Figure 9—1. **Hiring to replace anticipated retirements is expected to be close to 1500 controllers per year for the next decade.**

Staffing flexibility is restricted by the limits on a trained controller's qualifications. A controller's training certifies them to work on only a small number of sectors. This makes it difficult to respond to seasonal variations and localized spikes in retirements. Controllers are certified to work only the sectors within one area of specialization, or a group of 5-7 sectors within a Center. Figure 9–2 illustrates the sectors and areas of specialization within Kansas City Center. Transferring a controller to a new area of specialization requires significant retraining time and effort.

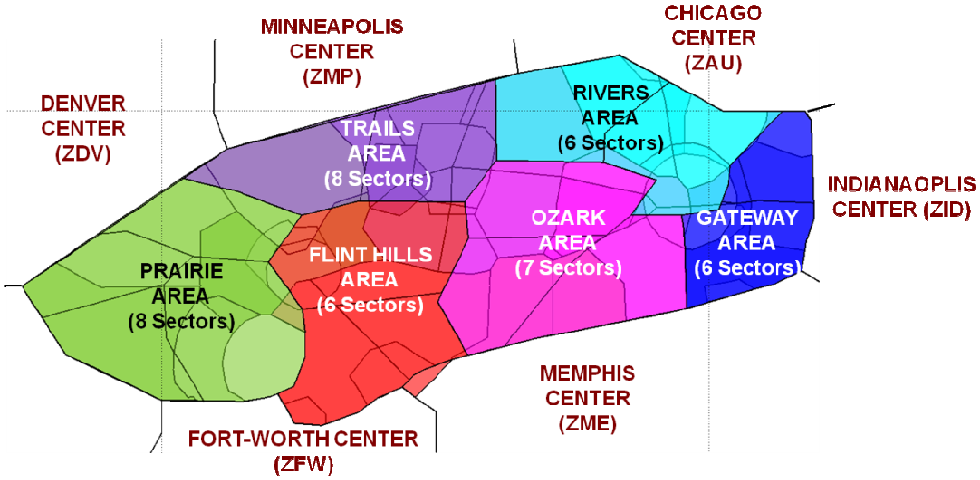


Figure 9–2. **Example of areas of specialization within Kansas City Center (ZKC).**

9.2 Methodology: A Cognitive Review of Controller Training

In order to identify opportunities for improving the controller training process, a cognitive and operational analysis was performed. The analysis reviewed *ab initio* and experienced controller training processes from the context of the cognitive process model shown in Figure 9–3. The review considered how trainees learn the effects of structure and how training develops structure-based abstractions.

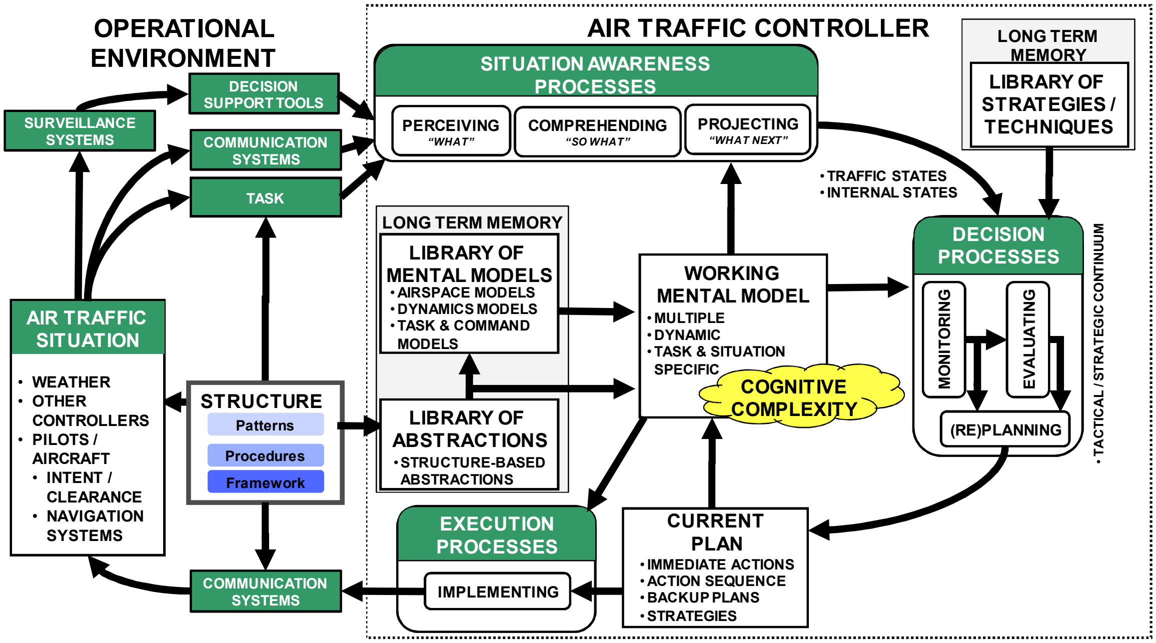


Figure 9–3. Cognitive process model.

Current training protocols used in both academic and on-the-job training stages of controller training were obtained. Based on a review of the protocols, key steps in the development of controller mental models and techniques used to teach structure were identified. The review examined all available material including statements of course objectives, syllabi and evaluation criteria. Training curricula, standard operating procedures, and study material provided to trainees were also reviewed. Data on minimum training hours, Monitor Alert Parameter values, and operational error rates were obtained in order to investigate how sector characteristics impact controller training.

As part of the analysis, focused interviews were conducted with training department personnel, facility training managers, and instructors (Table 9–1). Most interviews were conducted during site visits at the FAA Academy in Oklahoma City, and Washington Center; two interviews were conducted on the telephone. Questions asked during focused interviews during these site visits are listed in Table 10–4 in Appendix I. Questions focused on understanding how structure is taught; additional questions probed how complexity mitigation and control strategies are learnt and taught. Questions also probed for differences in the structure between sectors and how this affected training.

Table 9–1. Participants in focused interviews in support of review of enroute training.

FACILITY	FACILITY TYPE	INTERVIEWEES	NUMBER
Washington Center	**ARTCC**	Enroute controllers	**2**
		Training Manager	**1**
		Training Specialists	**4**
FAA Academy	**Training Academy**	Training Personnel	**5**
Indianapolis Center	**ARTCC**	Enroute Controller/Supervisor	**1**

9.2.1 Current En Route Training Process

The first step in the review was the development of a comprehensive representation of the current en route training process. A detailed depiction of the content and time invested in each stage of training is presented in Appendix V. A summary overview of the training process is shown in Figure 9–4. Stage I of training occurs at the FAA Academy (Academy) in Oklahoma City and is comprised of two courses. The first, "Air Traffic Basics", provides an initial introduction to concepts such as weather reporting and basic aircraft performance characteristics. The second course, "Initial En Route Training" provides a mix of classroom, part-task simulator, and high fidelity simulation exposure, primarily for the D-side position.[41]

Following graduation from the Academy, trainees begin training at their assigned facility. At the Center trainees proceed through three distinct stages. Stage II trains controllers on flight data responsibilities and how to perform the role of an A-Side, or assistant controller (Section 3.1.3). Experienced controllers transferring to a new facility begin their training at this stage.

Stage III provides training on the D-side position for each sector within the trainees area of specialization. This stage consists of classroom, computer based, and on-the-job training. Trainees must certify on the D-side position for each individual sector in the area of

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[41] Chapter 3 described the various positions on a sector team. See Section 3.1.3.

specialization. Stage IV provides similar training steps for the R-side position for the same set of sectors.[42]

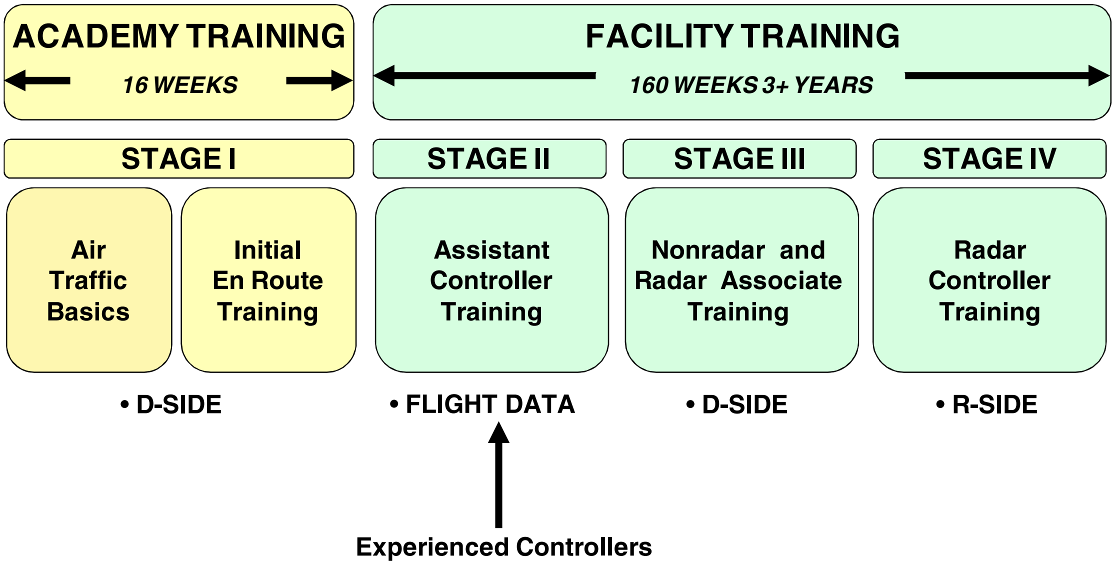

Figure 9–4. Overview of current enroute training process.

9.3 Key Findings

Three key findings emerged from the cognitive review. The review showed learning airspace structure occurs primarily through two mechanisms: map drawing exercises, and on-the-job training. Each of these mechanisms appears to be the primary pedagogical technique by which, respectively, framework layer and procedure/pattern layer structure is learnt (Figure 9–5). The review also showed that there are significant differences in the structure between sectors. These differences create sector-specific operational factors and the need for sector specific mental models.

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[42] Several Centers, Chicago, New York, and Houston, have experimented with a revised training order that varies slightly. After completing the first two D-side sectors, trainees are trained on the R-side position on the same sectors, and alternate between D-side and R-side positions henceforth.

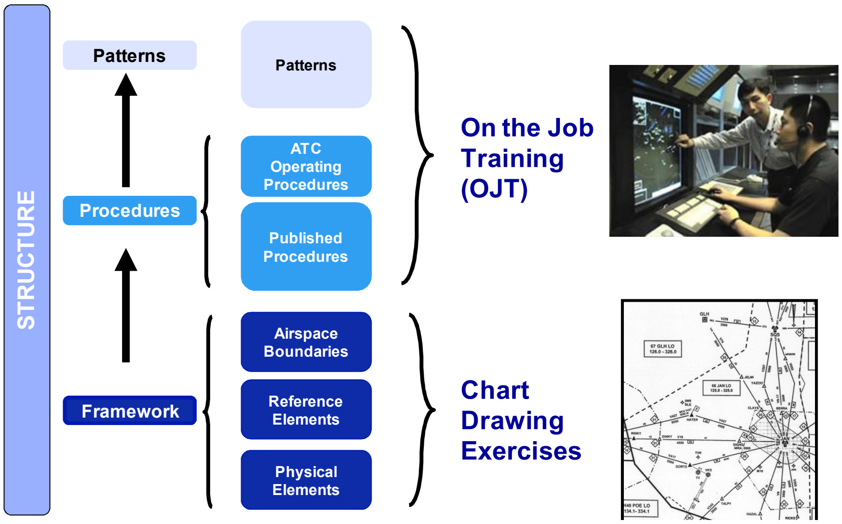

Figure 9–5. **Two key pedagogical techniques used for teaching structure.**

9.3.1 Chart Drawing Exercises are Key Pedagogical Technique for Learning Framework Layer Structure

The primary pedagogical technique used to teach framework layer structure is a series of chart drawing exercises. These chart drawing exercises are a key step in the initial development of mental models of the airspace and form a foundation that subsequent training steps build on.

The chart drawing exercises are a series of four exercises where trainees memorize and reproduce airspace maps. The timing of the exercises in the training process are shown in Figure 9–6. The chart drawing exercises are one of the first components at each training stage. As the trainee progresses through the stages the exercises become progressively more specific to the airspace the trainee will be controlling.

The chart drawing exercises follow a common format. At each stage trainees are given a blank template map. An example of the blank template for the airspace learnt at the Academy is shown in Figure 9–7. The blank template depicts the location of VORs which form central anchors around which trainees must draw framework layer structural elements. A complete Academy chart is shown in Figure 9–8. Elements that must be drawn include airways, intersections, distances for airway segments, and minimum altitudes (FAA, 2005b). The requirements for each chart are shown in Figure 9–9. Approaches and missed approaches are also memorized and drawn.

The level of detail on the charts increases as trainees progress through the training process. The Academy airspace requires memorization of approximately 300 distinct elements. Counts of elements on Center and area of specialization charts, examples of which are shown in Figure 9–10 and Figure 9–11, showed up to 1500 distinct information elements are memorized.

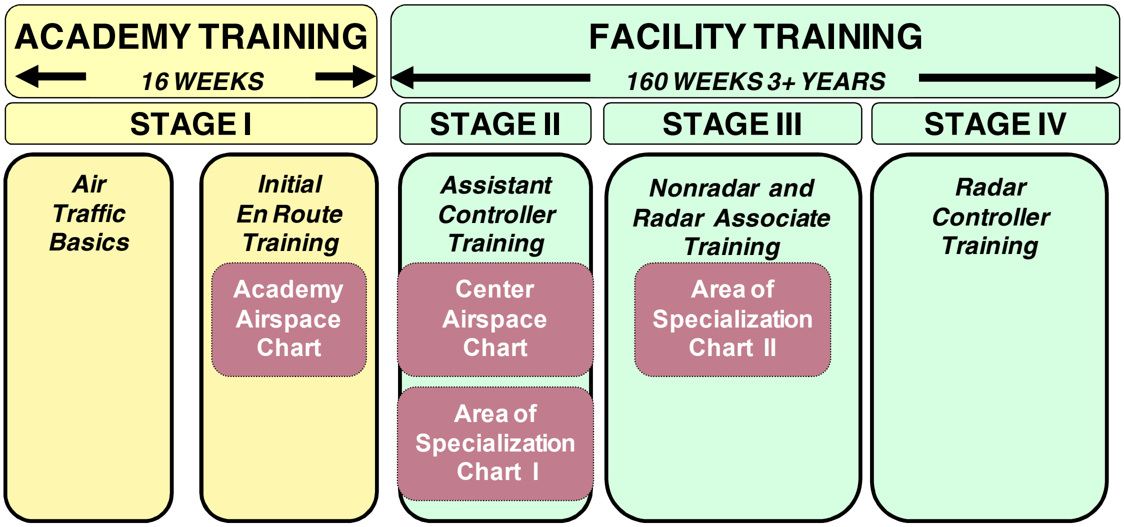

Figure 9–6. Progression of chart drawing exercises.

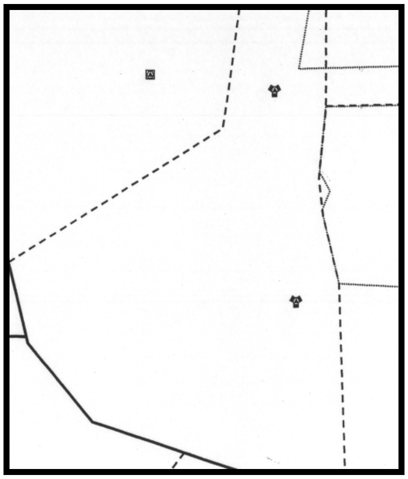

Figure 9–7. Academy airspace “blank” chart.

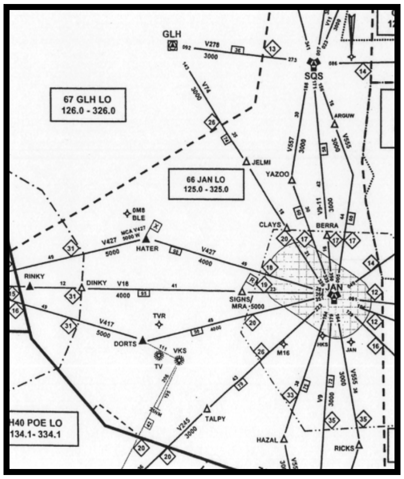

Figure 9–8. Academy airspace chart.

STAGE II
Assistant Controller
(Flight Data)

Center Area Chart.

- Label each NAVAID/fix with its correct identifier (including the first NAVAID outside the area).
- Depict all airways and jet routes extending from the first NAVAID/ fix outside the area and label each.
- Depict and identify sector boundaries.
- Depict and identify special use airspace.
- Identify adjacent center sectors.

Area of Specialization Chart I

ABOVE AND

- Indicate total mileage between NAVAIDs and/or fix posting.
- Depict and label all intersections.
- Depict and label restricted, prohibited, and warning areas and other special use airspace
- Depict and label all approach control airspace, VFR towers, FSS locations, and class B, C, D, and E airspace.

STAGE III
Nonradar & Radar Associate
("D-side")

Area of Specialization Chart II

ABOVE AND

- Label all MEAs, MRAs, MOCAs, and MCAs.
- Depict and label … for … airports within the area of specialization …:
  - Published holding pattern direction and turns.
  - Initial penetration/approach altitude.
  - Initial penetration/approach fix.
  - Outbound and inbound heading/bearing/radial.
  - Direction of procedure turn (if applicable).
  - Missed approach procedures and altitudes.

Figure 9–9. Requirements of chart drawing exercises (FAA, 2005b).

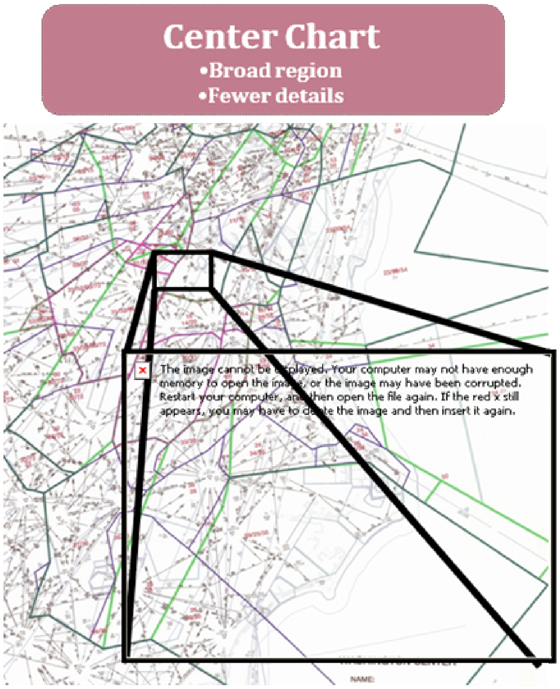

Figure 9–10. Center chart.

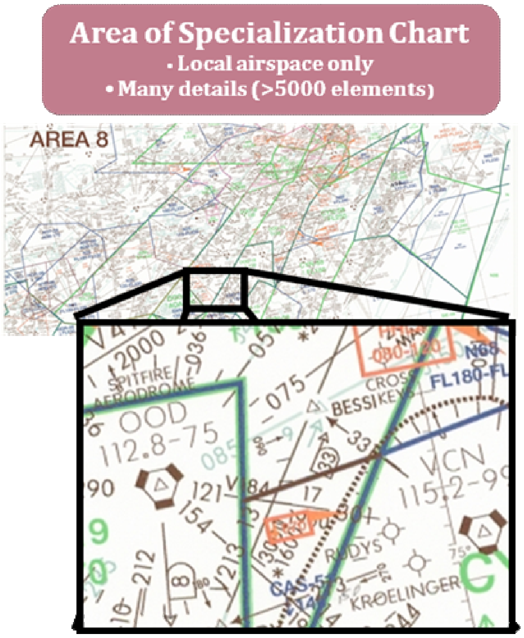

Figure 9–11. Area of specialization chart

The review showed that the chart drawing exercises are the primary pedagogical technique used to teach framework layer structure. Based on participant responses in the focused interviews, several key objectives of the chart drawing exercises were identified. A primary objective is the creation of an initial foundation within the controller's mental model of location and path references, their relative positions, and relationships with other elements of framework knowledge. The chart drawing exercises force trainees to internalize the relationships between fundamental and critical elements of framework layer structure. As Brown (2005b) describes "the important part is the spatial relationship [the chart elements] have to each other in relation to the framework of the VORs." Subsequent training steps assume and rely upon trainees having developed initial mental models of the airspace structure. The charts are frequently referred to as maps; a common and repeated complaint of instructor's in subsequent simulation and on-the-job training (OJT) steps was the barriers to training created by trainees "not knowing their map."

A second objective of the memorization process is the forced internalization of time critical information. Participants in the interviews reported that having access to information such as communication frequencies and altitude limits of a sector is time critical. Not having immediate recall of such information makes implementation of handoffs more difficult and creates challenges for evaluation and planning processes.

Finally, all controllers at the facility perform the common Center chart drawing exercise. This creates the basis for shared mental models across the facility. Common, shared, mental models are important enablers of controller communication. During handoffs and points and other coordination tasks, commonly understood references points facilitate simpler, more effective controller-controller communication.

9.3.2 OJT is Key Technique for Learning Procedure and Pattern Layer Structure

The cognitive review showed that the knowledge of framework layer structure formed an important building block for the development of abstractions reflecting elements of structure in higher layers of the structure hierarchy. The review showed that knowledge of the higher layers of structure and the development of structure-based abstractions occurs primarily through on-the-job training (OJT). OJT instruction consists of a trainee working a sector under the supervision of a certified controller acting as an instructor. The trainee performs the tasks of the position while being coached by the instructor. OJT is an apprenticeship style of training, with trainees learning tips, techniques and strategies from the instructor.

The review showed that it is primarily through the OJT process that trainees are exposed to sector specific procedures and patterns. Generic versions of procedures, practices, and standards are taught in classroom settings; for one or two initial sectors, simulation training provides initial exposure to the sector-specific procedures. However, the limitations of current simulation capabilities results in most of the learning of procedures and particularly patterns in a sector occurring in the OJT portion of training.

Thus, OJT plays a key role in exposing trainees to strategies and techniques as well as when those strategies or techniques should be applied. It is also the primary means by which trainees are exposed to and develop an understanding of how and when to apply knowledge of the structure within a dynamic operational environment. OJT helps trainees recognize the circumstances where particular strategies or techniques are appropriate and effective. Experiencing and developing a recognition of how structural elements in all layers of the structure hierarchy interact and affect the dynamics and task is a critical outcome of the OJT processes. OJT is the primary mechanism by which trainees develop mental models and abstractions that allow them to project, evaluate, and plan in ways that account for the broader context of the sector, including sector specific patterns and procedures.

The review also showed that OJT is the primary pedagogical technique used to develop mental models of how procedures affect the dynamics of aircraft and the implications for both their own and neighboring sectors. The observation of the importance of the Area of Regard (Chapter 4) shows that the operational context extends beyond the formal sector boundary. The effectiveness and appropriateness of strategies and techniques also depends on the constraints controllers of surrounding airspace are operating under.

Controller use of strategies is adaptive to changing conditions; an important part of OJT is teaching trainees strategies, mental models and abstractions incorporating the interaction between static elements of structure and dynamic parts of the environment, such as wind or weather events. Figure 9–12 depicts an example presented by a participant during the site visit at Washington Center of the need to develop such strategies. Under nominal conditions, the Sector B controller can issue a descent command in order to make an aircraft meet the crossing restriction at the boundary between Sector B and Sector C. However, a strong tailwind reduces an aircraft's "effective" rate of descent requiring the controller of Sector B to use strategies that are based on coordinating earlier descents with Sector A. Developing such strategies is not as simple as learning to coordinate: due to the unique sector geometries and traffic configurations, trainees have to learn to account for the implications of the lower altitude at entry into their own sector, as well constraints in Sector A that can affect their ability to give earlier descents.

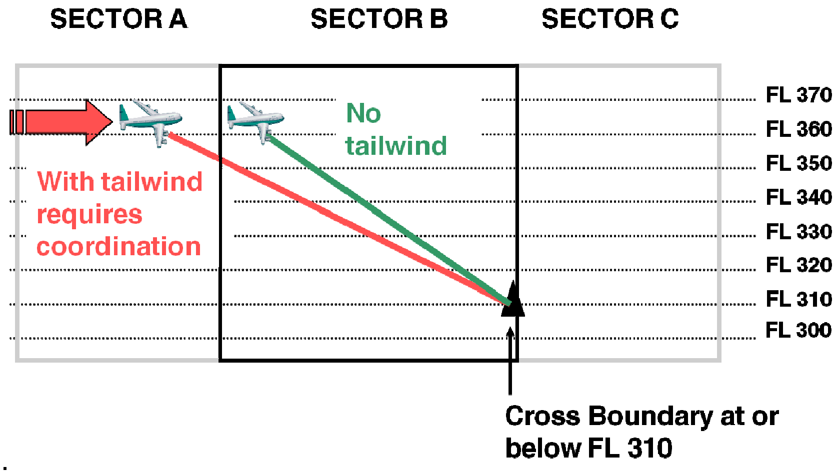

Figure 9–12. Relationships between weather and static structure.

Thus, a key aspect of learning when to apply strategies and techniques is developing abstractions and mental models that account for the sector-specific relationships between structural elements. Knowledge of these relationships, or the sector-specific context in which the structural elements exist, is distinct from knowledge and abstractions of the specific structural elements themselves. In turn, knowledge of the specific structural elements in a sector is distinct from broader abstractions of the generalized structural element.

Figure 9–13 illustrates these distinct levels of knowledge using holding procedures as a specific example. The top of Figure 9–13 shows the generalized, or basic, knowledge of the procedure. This knowledge is generic and at a high level of abstraction; for the specific example in Figure 9–13 this level constitutes general knowledge of holding procedures and standard race track patterns.

The middle of Figure 9–13 shows the knowledge of the detailed, sector-specific procedure. Knowledge at this level constitutes references to specific structural elements in the sector, including the mechanics of how to implement the procedure. As well, sector-specific parameters such as which VOR the holding pattern is based off of, as well as the radials, acceptable holding altitudes and other details form knowledge at this second level.

The final, most critical and difficult to train, level of knowledge is knowledge of how to apply the previous levels in the context of the sector. The contextual level is knowledge of how the procedure fits into the operational context of the sector. It encompasses knowledge of the relationships between the different structural elements in the sector and how they impact, influence, restrict, and constrain each other. In the specific example in Figure 9–13, aircraft in the holding pattern may constrain the altitudes or routes available to departures from the Albany airport.

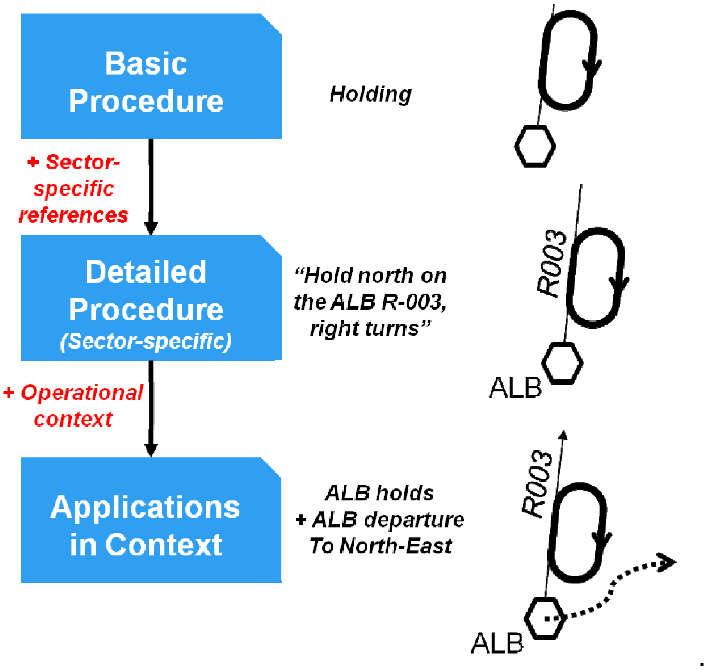

Figure 9–13. Knowledge of structure is required at multiple levels.

While OJT is valuable, there are several challenges that reduce its efficiency as a pedagogical technique. OJT is conducted in the 'real' environment, making it difficult to control a trainee's exposure to particular events and conditions. The actual flow of traffic determines the training scenario a trainee receives. This makes it challenging to ensure trainees have experienced the critical situations unique to a sector. Off-nominal conditions, by definition, occur relatively infrequently making it challenging to use OJT to teach how elements of structure interact and to develop the contextual knowledge to safely control them. For example, experiencing runway closings due to snow clearing operations in July, or thunderstorms in January, are very unlikely events.

A second important challenge for using OJT to develop knowledge of procedure and pattern layer structure is balancing the need to give trainees opportunities to learn and recover from mistakes while ensuring the instructor is still capable of stepping in to "save" the situation. Interview participants discussed the need to allow trainees to get themselves into, and out of, trouble. Formally the instructor's license as a controller is on the line, and any losses of separation are ultimately their responsibility. This provides barriers to trainees learning from mistakes, thus reducing the efficiency of the training.

Finally, the review identified the potential mismatch between instructor and trainee mental models as an additional challenge. With substantially different backgrounds and experiences, instructors and trainees will draw on very different libraries of abstractions and mental models. Trainees and instructors will perceive situations differently, and represent those situations within their mental model in very different ways. A key challenge in delivering effective OJT is ensuring that instructors are able to recognize these differences, tailor their instruction to how trainees are perceiving the situation, and thereby help trainees develop more sophisticated abstractions and mental models.

9.3.3 Multiple Sources of Sector, Situation and Task Specific Mental Models and Strategies

A third key finding from the cognitive review was the rich and diverse sources of differences in the structure between sectors. These differences create the need for sector-specific mental models and strategies. As described by one controller, “all airspace has little quirks.” (Brown, 2002a). There are over 750 distinct sectors within the United States. While the generalized tasks performed in each sector are similar (Chapter 3), the specific tasks, mental models, strategies, and abstractions required to perform those tasks can differ significantly. A significant portion of OJT is focused on learning local procedures, and practices, and developing mental models appropriate for those environments.

During the focused interviews, five participants were asked to “describe some specific sectors and examples of events and/or conditions that, in your opinion, it is important for a developmental to experience as part of the training process.” Detailed responses from the participants were consolidated to identify key factors that create unique, sector-specific conditions that generate the need for specialized and location specific mental models, strategies, and training. Figure 9–14 presents factors identified by more than one participant. The following sections briefly describe each sector specific operational factor.

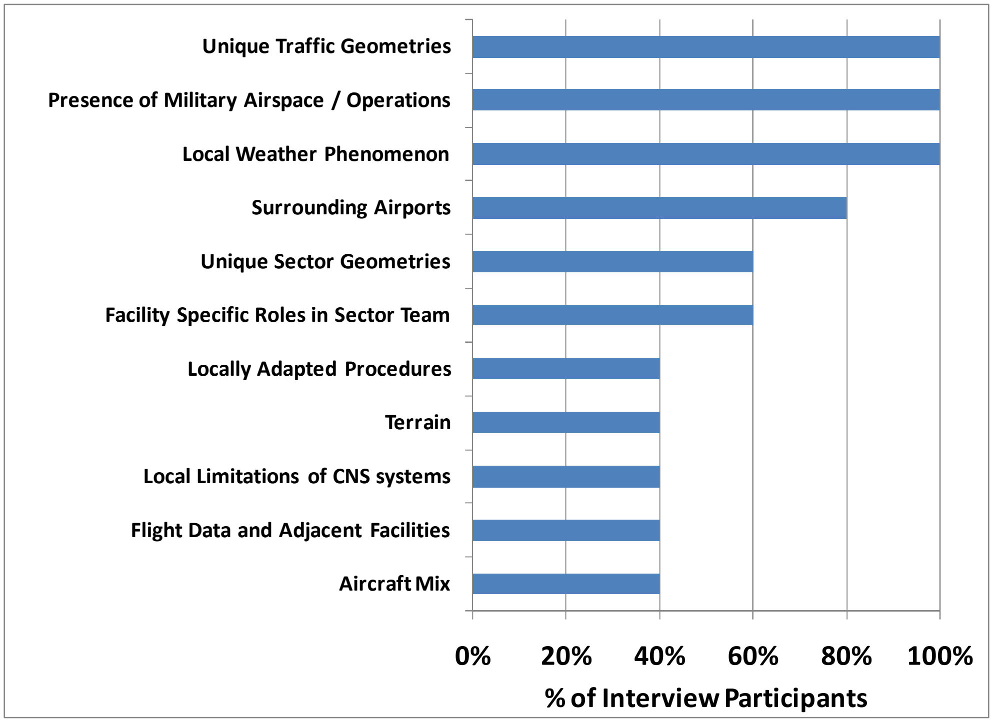

Figure 9–14. **Sources of sector-specific operating factors and local operational pressures create a need for unique mental models.**

Unique Traffic Geometries. The traffic patterns within each sector are different and create unique traffic geometries. While almost all sectors contain standard flows, the number and characteristics of the crossing points, merge points, and other key patterns in each sector varies widely. Differences in vertical behavior are a key source of the need for mental models adapted to the specific traffic geometry of a sector. The proportion of aircraft climbing or descending, and hence the appropriateness of grouping abstractions based on discrete altitudes, is often very different between sectors in the same area of specialization. For example, within the high altitude sectors of Boston Center, the percentage of aircraft in level flight through the sector ranges from 40 to 70 % (Figure 9–15).

Presence of Military Airspace / Operations. Participants universally identified the presence of military airspace and operations as a key operational factor. Military airspace represents obstacles for much of the traffic in a sector as well as a source and sink for military aircraft. Developing mental models capturing unique characteristics of the arrangements of the SUA is a key consequence of this sector specific operational factor.

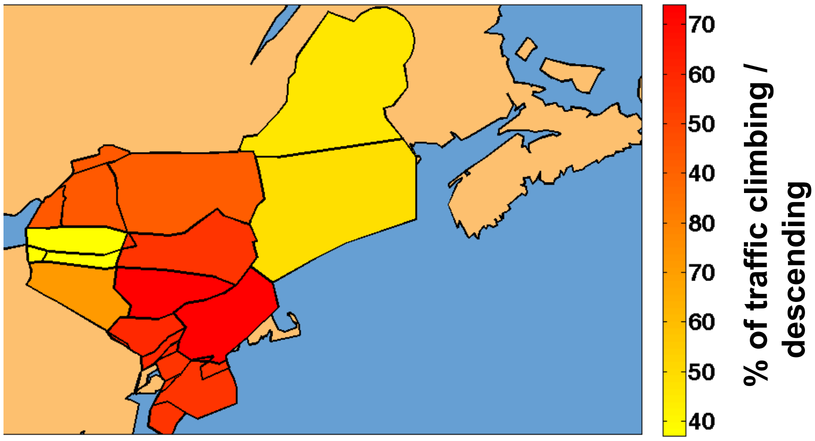

Figure 9–15. **Percentage of traffic climbing / descending within Boston Center high altitude sectors.**

Local Weather Phenomena. Local weather phenomenon impact pilot behavior and aircraft performance characteristics. Region specific effects, such as mountain waves, create pilot behaviors that modify aircraft dynamics. In addition, as discussed above, interactions between the static airspace structure and weather phenomenon can create the need for site specific strategies adapted to the changed dynamics in the situation.

Surrounding Airports. The distribution of airports in, near and around a sector was identified as a key factor creating a need for sector-specific mental models. As sources and sinks of aircraft, airports play key roles in determining the overall traffic patterns in a sector and the typical relationships between aircraft. In addition, low altitude sectors sometimes control the airspace above small airports without approach control facilities, or take over an approach control's airspace during late night operations. This adds new tasks as controllers must provide approach control services. In many cases, providing services to such airports requires application of non-radar rules and procedures. A controller must develop mental models of the relationships between approaches, missed approaches, and how operations at one airport can restrict others. Figure 9–16 shows the intricate relationships that are present between approaches to the airports in Denver's "ski-country"

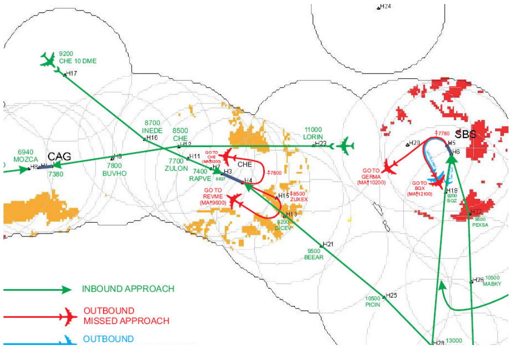

Figure 9–16. Approaches to airports in close proximity can overlap (from Dyer, 2007).

Unique Sector Geometries. The uniqueness of sector shapes and altitudes is a key factor dictating the need for specialized mental models. As illustrated in Figure 9–17, sectors come in a variety of shapes and sizes. In many cases, sectors contain small additions and subtractions to sectors in the form of "shelves." Shelves reduce coordination requirements by minimizing the number of frequency changes an aircraft must make. However, the rampant use of shelves makes sectors unique and creates its own training challenges; one area of specialization in Washington Center was reported to have 52 distinct shelves, each of which must be memorized and drawn as part of the chart drawing exercises.

The vertical extents of sectors vary widely and affect the typical aircraft in the sector (e.g. general aviation vs commercial), the types of tasks a controller must perform, and the ease with which altitude changes can be used as resolution maneuvers. As an illustration of the range in the vertical extents of sectors, Figure 9–17 shows the low and high altitude sectors across the United States; sectors with darker colors indicate sectors with more discrete altitude levels. As can be seen from the figures, the vertical stratifications of sectors varies widely between Centers and within Centers, creating a need for locally adapted mental models and strategies.

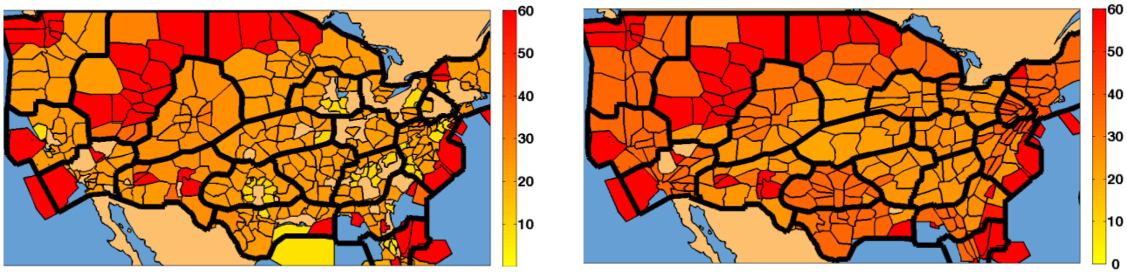

Figure 9–17. Number of altitudes (thousands of feet) in low (left) and high (right) altitude sectors.

Facility Specific Roles in Sector Teams. Mental models must also be adapted to differences in the way tasks are distributed between members of the sector team. Differences exist in the way tasks are distributed between the R-side and D-side roles; tasks such as flight strip marking, computer data entry, data block manipulation, and coordination with other controllers are distributed to the R-side and D-side positions differently.

The use of extra controllers during particularly busy or complex traffic periods also varies in both name and function. Additional controllers are known as "handoff" (Fort Worth Center) or "tracker" (Seattle Center) or "liaison" (Washington Center) positions. Their duties, responsibilities, and even seating positions differs between facilities. In some facilities the extra controller stands back and observes as an extra set of eyes; in others, the extra controller is given command of the keyboard and relieves the R-side and D-side controllers of data entry and flight data management tasks.

Locally Adapted Procedures. In general, the types of procedures are consistent across facilities; however, controllers must develop mental models incorporating local adaptations. Local adaptations simplify coordination requirements at sector interfaces and clarify responsibility for aircraft near boundaries. For example, some sectors have procedures explicitly allowing controllers to maneuver aircraft within the formal boundaries of another sector. Knowing which aircraft, under what conditions, and what control actions are permissible is important structural knowledge. In many cases, local procedures are the result of Letters of Agreement (LOA) that govern the interfaces between facilities. LOAs are highly specific to the local flows and military operations.

Terrain. Local terrain features were also reported as a sector-specific operational factor. Primarily of concern to low-altitude sectors, local terrain impacts minimum altitudes that can be assigned to IFR aircraft. Different facilities present distinct challenges: one interview participant contrasted the 30 distinct minimum altitudes within Fort Worth Center with the 103 applicable within Seattle Center. Minimum altitudes can force controllers to use different vector patterns and altitude step down techniques to control aircraft approaching an airport from different directions. Terrain effects were also reported as being the sources of changes in pilot behaviour. In mountainous terrain, pilots were reported to be more likely to slow down due to the presence of turbulence and chop. Such changes in aircraft behavior need to be learnt and incorporated into controller mental models and expectations of aircraft dynamics.

Local Limitations of Communication Navigation and Surveillance Systems. Local perturbations and limitations of communication navigation and surveillance systems are an additional factor creating a need for sector-specific mental models. Current radar surveillance techniques provide broad coverage at high altitudes but can be limited at low altitudes by terrain effects. The limits of radar coverage are often documented in sector standard operating procedures but interview participants suggested that practical limits are typically learnt as part of on-the-job training and through experience. Even in non-mountainous terrain, the available radar information can be limited as aircraft near the ground.

Interview participants also described the need to learn quirks and local knowledge about the precision of navigation references. Tracks flown by aircraft following an airway can differ from the depicted trajectory due to anomalies in navigation equipment and distortion of the VOR signals. Awareness of similarly named, and commonly mistaken, navigation references was also identified as key local knowledge.

Communication frequencies can sometimes overlap or interfere; it was reported that it can be important for trainees to learn to anticipate the potential for interference and confusion for pilots. Knowledge of the capabilities of backup and emergency equipment was also identified as key local knowledge. Backup frequencies do not always provide coverage to all of the airspace in a sector (Brown, 2005a).

Flight Data and Adjacent Facilities. A key part of the controller's task is managing flight data. Interview participants described local quirks of flight plan processing and the importance of understanding how flight data is transferred between facilities. Aircraft transitioning back and forth between multiple facilities in a short period of time appear to be particular sources of flight data trouble (Brown, 2002b). International boundaries present additional issues with both flight data passing and additional task requirements. Automation systems at the United States' northern and southern borders have limited capacity to perform automated hand offs of aircraft necessitating the passing of flight plan estimates and manual coordination.

Aircraft Mix. The types of aircraft in a sector are a final sector-specific operational factor. The mix of types of aircraft in some sectors can produce large speed differentials; recognizing and learning to manage "radically different descent profiles and speeds" was reported to be a sector specific operational factor. Sectors with a high proportion of military or general aviation traffic require distinct performance abstractions accounting for their dramatically different dynamics.

9.4 Opportunities to Improve the Efficiency of the Training Process

These findings as well as consideration of the cognitive process model, suggest several opportunities to improve the enroute training process. The following sections discuss these opportunities.

9.4.1 Introducing Generic Airspace and Procedures

Training times are lengthened by the need to teach sector-specific material (e.g. bottom two levels in Figure 9–13). Developing generic sectors that minimize the need for novel, sector specific mental models and strategies would reduce training times and making staffing more flexible. Deploying even a limited set of generic sectors has significant potential. Controllers certified and working a generic sector free staffing resources that can be used elsewhere in the system.

As discussed above, current airspace structure and procedures require the development of mental models that incorporate sector specific features. Controllers require significant "seasoning time," or exposure to and familiarity with local phenomenon and sector-specific operational features. Introducing generic airspace, by deploying standardized structure that minimizes the differences between sectors, is a significant opportunity to simplify training. Generic sectors can support easily transferred mental models, strategies and abstractions that preclude the need for specialized sector specific training and lengthy "seasoning time." A generic sector can be deployed across multiple areas of specialization or facilities, providing increased flexibility and responsiveness to local staffing shortfalls.

The most promising opportunities for deploying generic sectors are at high altitudes. High altitude sectors are less influenced by local operational pressures and the factors identified as being sources of sector-specific mental models. The mix of aircraft is more homogenous across high altitude sectors, and there are more consistent dynamics. This provides the best opportunity to develop structure and sectors that support transferability between sectors with minimal cross training.

The appeal of high altitude airspace has attracted other concepts. MITRE has proposed using experienced controllers to operate existing high altitude airspace in low traffic and complexity conditions. Feedback from controllers participating in initial human-in-the-loop experiments noted the importance of familiarization with the sector, particularly for higher traffic volumes and sectors containing climbing and/or descending traffic (Levin, 2007).

The generic high altitude sectors must be similar to each other but do not necessarily need to be identical. Aircraft manufacturers have successfully used standardized operations and procedures to minimize differences in training requirements between types of aircraft. For example, pilots qualified to fly the Airbus A340 require only a one day course to qualify to fly the Airbus A330. This cross-crew qualification approach standardizes key elements and uses "differences" training to teach remaining aircraft-specific knowledge. A similar approach can be used with generic airspace; deploying generic sectors that are similar enough that minimal differences training can be used to quickly certify a controller on the airspace.

There are many opportunities to modify structure to make sectors more similar. Based on the findings of the cognitive review, standardizing simple structural elements across sectors has the potential to reduce training times. Creating consistent structural elements that are common across all generic sectors reduces the memorization burden and can be ground work for more powerful opportunities. In the context of Figure 9–13 and the different levels of knowledge, standardizing a particular structural element reduces differences in the middle, sector-specific level.

Simple changes standardizing basic framework layer elements have benefits themselves but are also important building blocks for standardizing the patterns and procedures that define the operational context. More powerful opportunities arise from developing means of standardizing the higher layers of structure, procedures and patterns. The more standard the context, and the more consistent the relationships between the structural elements, the more appropriate standardized and widely applicable structure-based abstractions and mental models will be. Examples of changes include:

Opportunity: Sector Templates. Standardizing sector geometries creates commonalities in the airspace available and the scope of resolution maneuvers. However, differences in the underlying traffic patterns and demand for particular routings makes perfectly standardized boundaries operationally challenging. Identical sector geometries are not necessary to support similar abstractions making perfectly similar sectors less important. Rather than one size fits all, a limited set of standardized sector templates are a means of introducing similarity without rigidness.

Opportunity: Standardized Naming Conventions. There are opportunities to simplify reference elements in the framework layer of structure by adopting standardized naming conventions. Generic navigation and reference points with common spatial relationships provides a means of standardizing the context in which controllers perform the task. A consistent set of navigation and reference points makes implementation of commands easier (Mikolay, 2003). Standardizing communication frequencies is an additional opportunity to make more generic elements of structure.

Two examples of changes supporting more standardized sector-specific knowledge are:

Distribution of Reference Elements. As discussed in Chapter 8, new technologies are giving airspace designers the flexibility to design navigation waypoints at arbitrary points. Making consistent the distribution of such waypoints within the generic sector would promote standardized mental models of the airspace. Such consistency is an important building block for standardizing higher layers of structure. A consistent set of waypoints helps define a common route structure, ultimately making more consistent and common the standard flows through the airspace. Designing the underlying route structure to support similar flow patterns promotes common, easily transferable, abstractions.

Opportunity: Interface Procedures. Modifications to procedure layer structure can create more consistent and standardized interface procedures. Procedural changes can help standardize handoff locations relative to sector boundaries and establish consistent altitudes for crossing restrictions. Standardizing procedures governing operations at or near boundaries can help reduce the need for sector specific .mental models supporting point-outs and other coordination actions.

Challenges Associated with Generic Airspace

The cognitive process model was used as a basis to identify a preliminary set of challenges and human factors issues for the deployment of generic airspace. Key challenges that were identified include:

Challenge: Tradeoff between local operational pressures and standardization. Standardizing the structure and introducing more generic airspace would simplify the training process and increase staffing flexibility. However, local operational pressures create a tension between the standardization of underlying structure (e.g. procedures and airspace) and operational efficiency. Locally adapted procedures and airspace requires development of specialized mental models but can provide substantial capacity and efficiency benefits. Operations can be tailored to local constraints making the tasks in a sector simpler. As discussed, this comes at the cost of creating a need for site specific training and the development of specialized abstractions and mental models. Mitigating the consequences of changes necessary to surrounding airspace to accommodate the introduction of the generic sector is an additional challenge.

Challenge: How to determine similarity between sectors? The benefits of generic airspace are greatest when minimal differences training can be used to transfer controllers between similar examples of generic airspace. However, a key challenge is operationalizing the concept of similar sectors that support a transferable mental model. As discussed above, it is not sufficient to make sectors have consistent boundaries. Quantifying the concept of similar “applications in context” (Figure 9–13) is neither straightforward nor simple. Establishing metrics of similarity based on common patterns supporting important abstractions is a promising initial step. The presence and relationships of critical points and standard flows provides a starting point for developing such a metric.

Challenge: How does the generic airspace interface with surrounding sectors? As discussed in Chapter 4, controller attention, decision making and planning encompasses airspace beyond a sector's formal boundaries. Standardizing airspace may need to extend beyond a single, generic, sector's formal boundary and include standardization of neighboring sectors, including those sectors below the generic sector. The impact of combining and splitting neighboring sectors on controller mental models also presents challenges. The geometry of surrounding sectors may be a bigger factor than the boundaries of the generic sector itself; understanding who the controller needs to coordinate with, to whom, when and where aircraft are to be handed off, and what constraints the surrounding controllers are operating under are key challenges to developing a truly generic mental model.

Challenge: What impact do equipment and automation differences have on potential for generic airspace? As noted above, perturbations and quirks in communication navigation and surveillance equipment was identified as a key source of site-specific mental models. Insulating generic airspace from such idiosyncrasies will be a challenge; relationships with both internal and foreign ATC providers with different equipment and automation capabilities raises additional challenges.

9.4.2 Improving Teaching of Framework Structure

The goals of the chart drawing exercises are important and valuable. As the first step in each training stage, the chart drawing exercises are fundamental building blocks of controller mental models. Developing a deep understanding of the airspace is clearly important and valued by instructors in subsequent steps in the training process. However, the mechanism of memorization and regurgitation on the chart drawing exercise is often perceived as onerous and time consuming. Based on the cognitive review, there are several opportunities to improve the development of mental models of the fundamental framework layer structure of a sector. Four key opportunities are described below.

Opportunity: Reducing Memorization Burden. The amount of material memorized in the chart drawing exercises is daunting. Introducing new technologies and forms of framework layer structure as well as increasing the density of waypoints, all opportunities identified in Chapter 8, all have the potential to add to the material memorized. This is particularly the case when legacy forms of structure such as VOR based airways and jet routes are also retained.

There is an opportunity to streamline the content of the chart drawing exercises and focus it on material fundamental to building a mental picture of the sector. Core framework layer elements include airspace boundaries, relevant waypoints and navigational aids, and routes. Superfluous material that, while important, is not critical for developing a baseline understanding of how the sector works should be eliminated. Some elements, such as opening hours of restricted airspace have already been eliminated. New decision support tools provide further opportunities to offload structure knowledge from a controller to the operational environment. Tools such as the recently deployed En Route Information Display System (ERIDS) provide controllers with real-time access to graphical and textual products including approach charts, active traffic management initiatives, sector and facility standard operating procedures, airspace charts and Notices to Airmen (NOTAMs). Details irrelevant to the formation of a fundamental mental model of the structure of the sector should be considered for off-loading to these new decision support tools.

Opportunity: Advantage of Improved Display Capabilities. Reducing the memorization burden still leaves significant material to be learnt. The deployment of ERAM (En Route Automation Modernization) is adding new training simulation capabilities. There are opportunities to take advantage of these capabilities to better support learning of time critical information. During initial simulation sessions, the improved display capabilities can be used to overlay fix names, communication frequencies of surrounding airspace, and other information elements on the primary situation display.[43] This would supplement and reinforce controller mental models of key elements during initial familiarization with the sector.

Opportunity: Timing of Chart Drawing Exercises Due to the long training times within each stage, the content is often forgotten by the times trainees actually need and use it. There are opportunities to make the chart drawing exercise more effective by revising when they occur and what material is covered in each exercise. The value in memorizing the route segment distances for a sector that won't be controlled for six or more months is debatable. Introducing sector

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[43] Operational use of such capabilities is hampered by screen clutter and the potential for overlap of critical information. However, it would provide valuable reinforcement of trainee mental models during initial simulation settings and could be discontinued as required.

specific chart drawing exercises, conducted prior to simulation on OJT on each sector, would make the material on the exercises more relevant and subsequent training more efficient and effective. Requirements on the initial chart drawing exercises at each stage can be relaxed, reducing the time and memorization burden on trainees. Washington Center has implemented a variant of this; before proceeding to OJT on each sector, each trainee must draw the basic airspace map depicted on the situation display for that sector.

Opportunity: Alternative pedagogical techniques. The current chart drawing and memorization pedagogical approach is not the only, nor necessarily most effective, method of teaching and testing knowledge of structure. There are opportunities to expand the tools trainees are provided for learning airspace boundaries. Technological advances have greatly expanded the capability to visualize the complicated three dimensional boundaries of many sectors (e.g. Figure 3–3). Simple, controllable, zoomable and rotatable visualizations can help trainees understand sector boundaries and how the relate to each other and other structure elements. Other alternatives, such as physical blocks in the shape of sectors can help trainees learn to piece together the three dimensional aspects and support students with tactile learning style. Recognizing that a key objective of the current chart drawing experience is the development of mental models capturing how the pieces of airspace fit and work together opens many opportunities for creative teaching techniques.

9.4.3 Opportunity: Integrating R-side / D-side Training

Based on the cognitive review, a closer integration or R-side and D-side training presents opportunities to enhance the development of important trainee abstractions. An important step in the development of a trainee's mental model is understanding the roles and responsibilities of other personnel in the operational environment. Other personnel may be another controller on the same sector team or controllers working surrounding airspace. Understanding the roles of the other controllers, their expectations and mental models of the situation, task, and distribution of responsibility is a critical step in a trainee's development.

Currently, training at the Academy is focused primary on D-side tasks. At the facilities, trainees certify as a D-side on all sectors in their specialty before beginning R-side training. Earlier exposure and training on R-side operations while at the Academy should enhance trainees understanding of R-side roles and responsibilities. Earlier exposure to other controller roles, for example acting as the R-side during D-side training, would help trainees deeper mental models of the role of the R-side controller and how D-side actions help or hinder their task.

The development of the skills, techniques, and phraseology required for the R-side position will require the student to develop an understanding of how the R-side position thinks about the air traffic situation. One participant described this as "being [a] good D-side is more than just learning job – its learning [the] person next to you, get inside them, know what they are thinking." A good D-side is "able to already do the pointouts, already done coordination necessary before [the] aircraft is even on frequency."[44] Understanding the abstractions and cognitive approaches used in the R-side role allows trainees to develop a better awareness of the needs of the R-side and how the D-Side position can best support him or her. This in turn, will produce a trainee that will perform more effectively as a D-side once they reach the facility-specific stage of training.

Care must be taken that the instructional value of each training scenario is maintained for the D-side even with a novice in the R-side position. Instead of only learning from one's own mistakes, trainees would be exposed to a variety of sources of errors and the learning objectives of each lesson may become obscured. The creative use of staggered scheduling, such that trainees nearing the end of their Academy course are paired with a class of trainees just beginning the high-fidelity scenarios, is one means of addressing this challenge.[45] As well, the students currently participate in paired training activities during the partial task section of the course without any apparent impairment to their training progress.

Other challenges with earlier integration of R-side and D-side training include the potential of overloading trainees early in the training process. The introduction of additional material to learn may degrade the students' ability to absorb and apply the existing material, increasing the failure rate. In addition, the significant differences in the projecting, evaluating, and planning processes and tasks between the D-side and R-side positions makes it important to ensure that additional training is not confusing and a distraction. Providing parallel R-side and D-side training may lead to student confusion and application of inappropriate abstractions in either role. It is important to ensure that the basic skills and abstractions used in the D-side position are well grounded and developed before introducing those required for the R-side position.

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[44] Indianapolis Center, Air Traffic Controller

[45] Using staggered experience levels might partially alleviate this issue, but would face its own challenges including designing scenarios that are both simple and complex for the different positions.

9.5 Summary

The cognitive process model, structure hierarchy, and identification of controller use of structure-based abstractions are useful tools for examining the en route controller training process. Based on a cognitive review of current en route training processes, three key findings were identified. A series of chart drawing exercises are the primary pedagogical technique for teaching framework layer structure. These exercises establish the foundation of a controller's mental model of the airspace. OJT is the primary pedagogical technique by which trainees learn the procedure and pattern layers of structure. A simple, notional, model of different levels of knowledge of structure was presented; the model captures important distinctions between general knowledge, knowledge of a sector-specific instance of the structure, and knowledge of the context in which the structure operates. The third key finding was the identification of sector specific operating factors and sources of local operational pressures that create a need for sector specific mental models and abstractions.

Multiple opportunities to change either the operating practices, and /or the training process emerged from the cognitive review. The deployment of more generic airspace and introduction of differences training provides opportunities to significantly increasing staffing flexibility. New decision support tools provide opportunities to offload structure knowledge from the controller to the operational environment. New pedagogical techniques and changes to the timing and level of detail would make the chart drawing exercises more effective and efficient while preserving the establishment of a fundamental mental model.

CHAPTER 10 Thesis Summary and Conclusions

10.1 Thesis Summary

Approach and Identification of Structure

A cognitive ethnographic approach was used to examine the cognitive demands of the work and task environment of the air traffic controller. Focused interviews, site visits, and analysis of traffic data, standard operating procedures, and controller-pilot communications, created a diverse set of observations of cognitive complexity factors and elements of structure. The observations suggested that structure plays key roles in reducing cognitive complexity. Three distinct types of structure were identified and presented as part of a structure hierarchy: patterns, procedures, and framework layers.

Incorporation of Structure into Cognitive Process Model

The observations and previous literature informed the development of a cognitive process model incorporating structure's influences on the air traffic situation and its dynamics, the task, and the commands issued through the communication system. The model also incorporates influences on abstractions simplifying the controller's working mental model and strategies and techniques used in decision processes.

Structure-based abstractions

As simplifications of the working mental model, structure-based abstractions are a key link between structure in the operational environment, and the reduction of cognitive complexity. Based on one or more elements of structure in an air traffic situation, structure-based abstractions are a controller's internalization of the influences of structure on the dynamics of an air traffic situation, on available commands and the task. Structure-based abstractions allow controllers to use working mental models that are as effective as, but less cognitively demanding than, detailed representations of an air traffic situation. Based on the observations, four types of structure-based abstractions were identified: standard flow abstractions, grouping abstractions, critical point abstractions and responsibility abstractions.

Simplification Mechanisms of Structure-based Abstractions

Multiple mechanisms by which structure-based abstractions can simplify a working mental model were identified. Mechanisms include reducing the order or degrees-of-freedom of the working mental model, supporting decomposition of the task, reducing the number of comparisons performed, supporting recognition of commands, and providing standardized dynamics.

Dynamic Use of Structure-based Abstractions & Controller Operating Modes

Observations and a review of the literature suggested the use of structure-based abstractions is fluid, flexible, and responsive to the current situation. Controllers can choose to not use the structure that is present, or impose their own, through commands and actions. The dynamic use of structure-based abstractions is consistent with air traffic controllers utilizing distinct operating modes. Four operating modes corresponding to changes in the use of standard flow and critical point abstractions were identified: an opportunity mode, a route structure mode, a congestion mode, and a system shock mode.

Experimental Probes of the Use of Structure-based Abstractions

Two aspects of structure-based abstractions were selected and probed in greater depth. The first area was the cognitive complexity reduction mechanisms behind structure-based abstractions. A simple part-task experiment investigated whether cognitive complexity can be reduced by explicitly changing the structure in a manner consistent with a hypothesized cognitive complexity reduction mechanism. The degrees-of-freedom of an air traffic situation was explicitly controlled by manipulating the presence of standard flow and critical point structural elements. Subjective comments, scenario rankings and performance suggest that the presence of structure which reduces the degrees-of-freedom of a situation decreased cognitive complexity, consistent with the hypothesized mechanism.

A second area probed was the dynamic use of structure-based abstractions and the effects of manipulating traffic levels on controller operating modes. A second part-task experiment examined how the use of the route structure and a merge point varied with the number of aircraft being controlled. Participants clearly transitioned between opportunity mode behaviors and route structure mode behaviors. Distinct changes in the types of commands used provided evidence of a transition from route structure to congestion mode.

Identifying Cognitive Complexity Considerations

The cognitive process model incorporating key influences of structure was shown to be a useful tool for identifying cognitive complexity considerations arising from changes to the structure. This was illustrated by analyzing the structural changes introduced by four opportunities to improve system performance and presenting examples of cognitive complexity advantages and challenges. Considerations common to more than one opportunity including minimizing the degrees-of-freedom, limiting the overall number of critical points, minimizing the number of critical points any one aircraft goes through, and preserving the availability of maneuvering airspace.

Identifying Opportunities to Improve Controller Training

The cognitive process model was also shown to be valuable through a cognitive review of the current en route controller training process from the perspective of structure. The review identified key pedagogical techniques by which trainees learn structure and develop structure-based abstractions. The review also identified opportunities to change either the training process and/or operational practices in order to improve the training process. Developing more generic airspace supporting transfers of structure-based abstractions, mental models between sectors is one opportunity that would reduce training times and provide more staffing flexibility.

10.2 Conclusions

Structure is an important factor in controller cognitive complexity. Structure impacts the task, the dynamics of the air traffic situation, and the commands available to the controller. It provides a basis for abstractions simplifying the controller's working mental model and enables strategies and techniques controller's can use to reduce cognitive complexity. The use of structure is dynamic and responsive to changes in the traffic being controlled.

Accounting for the impact of structure on controller cognitive complexity is critical for transitioning to new operating concepts or other improvements to the system. It is important to consider how modifications to existing systems, or the introduction of new systems, will affect the key influences of structure, and particularly its ability to support simplifying structure-based abstractions. The identification of the key influences of structure also provides opportunities to modify and/or design improved structure. Understanding the key cognitive complexity reduction benefits of structure also provides an improved basis for assessing improvements to the system and identifying important cognitive complexity considerations.

Finding an appropriate balance between imposing structure in order to provide cognitively manageable situations and providing the desired flexibility, efficiency and capacity is challenging. The cognitive process model provides a tool for evaluating the impact of structural changes and for considering how to provide the necessary structural support for use of key complexity reducing abstractions. This tool should allow system and airspace designers to improve the performance of the system, while maintaining safe operations.

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Appendix I. Focused Interview Questions

Table 10–1. Questions used in focused interviews of controllers.

AIR TRAFFIC CONTROLLERS
What are the key factors influencing complexity?
Please rank the sector's in this Area from most difficult to least?
What characteristics make a sector more / less difficult?
(TRACON only) What runway configuration makes this sector more difficult? What airspace changes would you make to reduce complexity?
What are some of the key elements of structure in this sector?
How do you use the structural elements in this sector?
Does structure reduce uncertainty? If so, how?
What techniques / tricks do you use in difficult situations?
What techniques / tricks do you use to cope with increasing complexity?
What are the "hotspots" in this sector?
(Supervisors) what are the operational factors you use to make a decision to open/close a position?
How far ahead are you looking / projecting at any one time?

Table 10–2. Questions used in focused interviews of traffic management unit personnel.

TRAFFIC MANAGEMENT UNIT PERSONNEL
What are the key factors influencing complexity?
What determines the values used in miles-in-trail restrictions?
What factors determine a decision to impose a flow restriction?
How do you evaluate the complexity of a situation?

Table 10–3. Questions used in initial focused interviews of training personnel.

TRAINING DEPARTMENT STAFF
What are the key factors influencing complexity?
What techniques do you teach controllers for dealing with difficult situations?
How are Standard Operating Procedures taught?
What knowledge base is required? How is it taught?
How are controllers instructed to build a plan? How is the planning process taught?

Table 10–4. Questions used in follow-up focused interviews of training personnel.

FOCUSED INTERVIEW QUESTIONS FOR TRAINING SPECIALISTS
People talk about the "picture" or the flick. What is your understanding of what this means?
How does a controller learn how to "get the picture"? What elements of the situation are observed? What background knowledge is used? What parts of the process of getting the picture do trainees have the most difficulty with?
What do you think are the most important differences between how a trainee and an experienced controller think about an ATC situation?
What strategies do controllers use to reduce the complexity of an ATC situation? For each strategy: How does a controller use that strategy to think about the ATC situation? How do you teach a controller to use that strategy? Does the use of the strategy vary by sector? How is the development of these strategies assessed during OJT?
How does a controller think about the 3 dimensional aspect of the airspace? How is a controller trained to think about the 3 dimensional aspect of the airspace?
In your opinion, what are the most important differences in how controllers think about the ATC situation in radar vs non radar environments? in the R-side vs D-side position?
Please describe the training protocol for a typical trainee. When do map drawing exercises occur? When do they receive non radar training? D-side and R-side training?
What do you think are the most important factors influencing the time it takes a trainee to master a position on a sector?
What airspace maps are trainees required to learn at your facility? In your opinion, what are the training objectives and teaching value of the map drawing exercises at your facility?
What is the importance of trainees drawing the maps from memory?
In your opinion, what is the training value of the non radar training at your facility? Do you think it is important for a trainee to receive non radar training before radar training? Why? How would trainee development in radar training be affected by the removal of non radar training at your facility? at the Academy?
What operational factors produce unique training needs specific to your facility?
Are there important operational experiences you feel a trainee must have before they can become qualified on a sector? Are these experiences specific to each sector? Could they be trained effectively in simulation? What are the advantages and disadvantages of performing OJT in a simulated environment?
What memory items must a "day-to-day" controller have in order to be an effective controller? Are there differences in the types of items between sectors?
In your opinion, what are the 3 most important opportunities to improve the training process?

Appendix II. Example Field Observation Form

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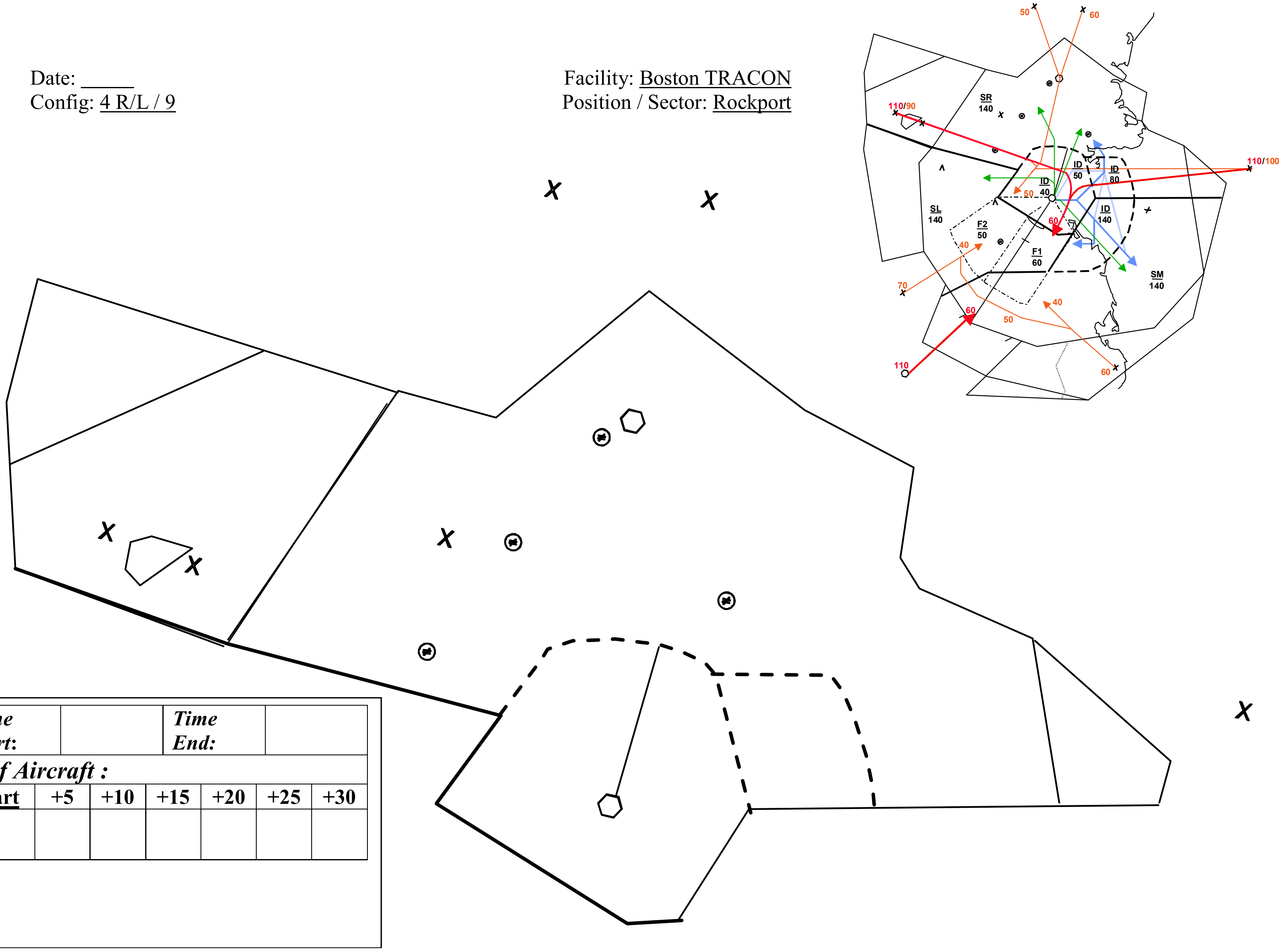
Date: ______
Config: 4 R/L / 9

Facility: Boston TRACON
Position / Sector: Rockport



Time Start:			*Time End:*			
# of Aircraft :						
Start	**+5**	**+10**	**+15**	**+20**	**+25**	**+30**

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Appendix III. Examples of Sector Standard Operating Procedures

Table 10–5. Examples of ATC procedures identified from sector standard operating procedures.

PROCEDURE CATEGORY	EXAMPLE
Routing requirements	"Sector 38 shall clear aircraft landing PVD and ISP to cross 85 east of HNK…"
Crossing restrictions	"Enter Sector 36 descending to or below 13,000 feet"
Control delegation	"Sector 05 has control for turns south on all aircraft on V270 east of DNY"
Coordination	"Sector 52 shall coordinate with Sector 08 prior to issuing an IFR departure clearance at SLK"
Sequencing responsibilities	"Sequence all EWR jet arrivals via HNK with EWR jet arrivals in Sector 23"
Holding	"Hold north on the ALB R-003, right turns"
Military airspace / Training routes	"When [Laser South] is under autonomous control, the aircraft shall be handed off to Sector 37. Sector 37 shall clear the aircraft into the block. …"
Automated handoff transfers	"…Casino Sector shall clear the aircraft to 17,000 feet within its airspace and update the data block with an interim altitude…. shall [then] initiate a transfer of radar identification to Sea Isle Sector"
Simultaneous approaches / Protected airspace	Any VSF approach and any CNH approach.

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Appendix IV. Coding Scheme for Controller-Pilot Communication Analysis

CONTENT TYPE	ABSTRACT FORM	PARAMETER 1	PARAMETER 2	PARAMETER 3
Command	Clearance	Clearance Type (Full Route / Approach….)	N/A	N/A
	Climb and Maintain	Assigned Altitude	N/A	N/A
	Cross <Fix> at <X> Feet	Crossing Point	Crossing Altitude	N/A
	Cross <Fix> at <X> Knots	Crossing Point	Crossing Speed	N/A
	Descend and Maintain	Assigned Altitude	N/A	N/A
	Deviate	Direction of Turn	Deviation Restriction	N/A
	Direct to <Fix>	Location	N/A	N/A
	Discretion (Altitude)	N/A	N/A	N/A
	Expedite	State to Expedite (Climb / Descent)	Expedite Detail	N/A
	Heading Change	Direction of Turn	New Heading	Magnitude of Heading Change
	Hold	Hold Location	Direction of Turns	Hold Details
	Intercept Arrival Route	N/A	N/A	N/A
	Rate of	Increase / Decrease	Rate Dimension (Climb/Descent/Turn…)	Rate Detail
	Resume Own Navigation	N/A	N/A	N/A
	Speed Command	Assigned Mach # / Speed	Restriction on Speed	Duration of Speed Assignment
Gathering Information	Asked Question	Question Details	N/A	N/A
Handoff	Check-in	Current Altitude	Assigned Altitude	N/A
	Check-out	Receiving Facility	Receiving Frequency	N/A
Instructions	Advise	Advise Detail (If need deviate / when slowing …)	N/A	N/A
	Change Frequencies	N/A	N/A	N/A
	Frequency Management	Frequency Management Detail (Standby/Go Ahead…)	N/A	N/A
	Maintain VFR	N/A	N/A	N/A
	Squawk	Squawk Type (1200/IFR/EMERG)	N/A	N/A
Other	Discussion	Discussion Subject	N/A	N/A
	Other	Details of Other	N/A	N/A
Providing Information	Altimeter Setting	N/A	N/A	N/A
	Explanation / Intent	Explanation Details	N/A	N/A
	Radar Contact	Radar Contact Detail	N/A	N/A
	Statement of Position	Distance From	Location	N/A
	Traffic Call	N/A	N/A	N/A
Roger / Acknowledgement	Roger or Other Acknowledgement	N/A	N/A	N/A
Unknown	Unknown Command	N/A	N/A	N/A
Ignore	Controller Voice Change	N/A	N/A	N/A
	ICAT Observer Comment	Comment	N/A	N/A

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Appendix V. Observations of Controller-Pilot Communications

Table 10–6. Sectors and sessions of communication data collected and analyzed.

Sector	Weather condition	Duration
Sector A		**11:36:16**
	Clear	7:21:20
	Convection	4:14:56
Sector B		**19:41:10**
	Clear	13:08:33
	Convection	6:32:37
Sector C		**15:05:18**
	Clear	10:34:27
	Convection	4:30:51
Sector D		**11:32:40**
	Clear	8:31:12
	Convection	3:01:28
Sector E		**10:00:49**
	Clear	10:00:49
Sector F		**6:01:51**
	Clear	6:01:51
Grand Total		**73:58:04**

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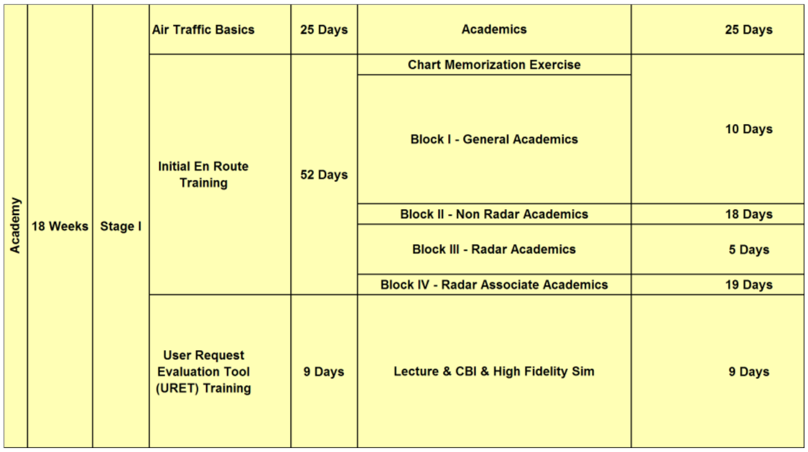
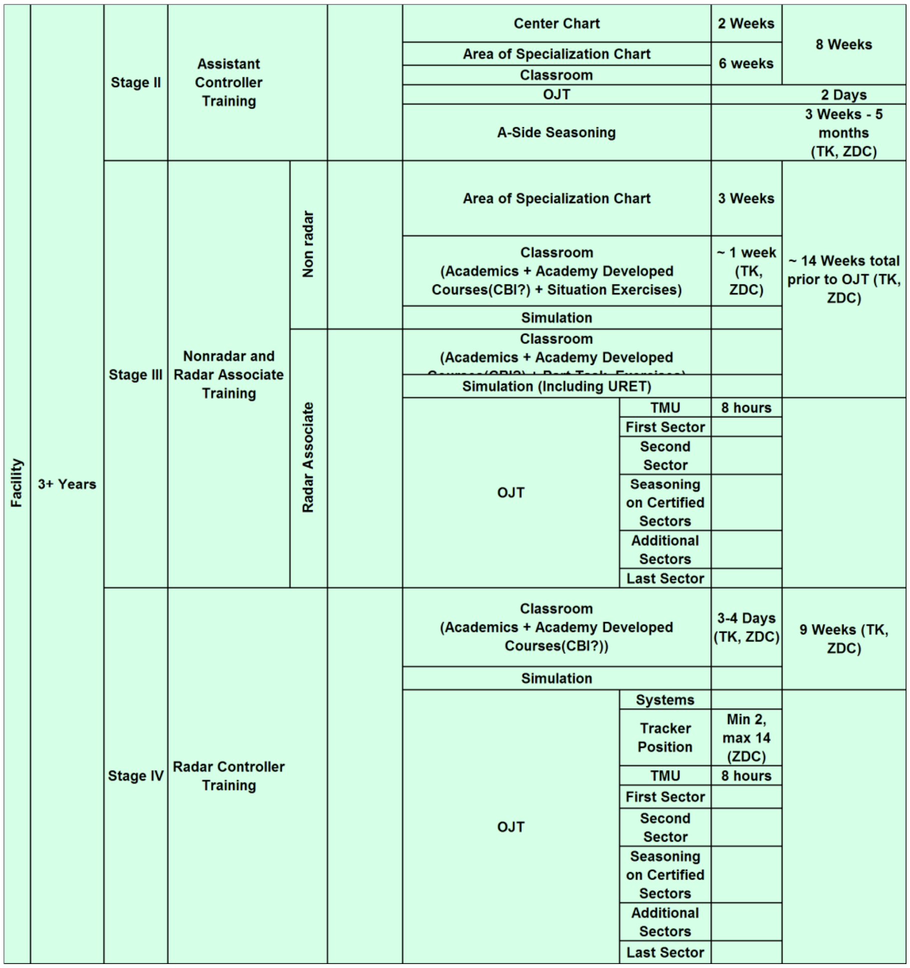
Appendix VI. Detailed Description of Enroute Controller Training Process



Academy	18 Weeks	Stage I	Air Traffic Basics	25 Days	Academics	25 Days
			Initial En Route Training	52 Days	Chart Memorization Exercise	10 Days
					Block I - General Academics	
					Block II - Non Radar Academics	18 Days
					Block III - Radar Academics	5 Days
					Block IV - Radar Associate Academics	19 Days
			User Request Evaluation Tool (URET) Training	9 Days	Lecture & CBI & High Fidelity Sim	9 Days



Facility	3+ Years	Stage II	Assistant Controller Training			Center Chart		2 Weeks	8 Weeks
						Area of Specialization Chart		6 weeks	
						Classroom			
						OJT		2 Days	
						A-Side Seasoning		3 Weeks - 5 months (TK, ZDC)	
		Stage III	Nonradar and Radar Associate Training	Non radar		Area of Specialization Chart		3 Weeks	~ 14 Weeks total prior to OJT (TK, ZDC)
						Classroom (Academics + Academy Developed Courses(CBI?) + Situation Exercises)		~ 1 week (TK, ZDC)	
						Simulation			
				Radar Associate		Classroom (Academics + Academy Developed Courses(CBI?) + Part Task Exercises)			
						Simulation (Including URET)			
						OJT	TMU	8 hours	
							First Sector		
							Second Sector		
							Seasoning on Certified Sectors		
							Additional Sectors		
							Last Sector		
		Stage IV	Radar Controller Training			Classroom (Academics + Academy Developed Courses(CBI?))		3-4 Days (TK, ZDC)	9 Weeks (TK, ZDC)
						Simulation			
						OJT	Systems		
							Tracker Position	Min 2, max 14 (ZDC)	
							TMU	8 hours	
							First Sector		
							Second Sector		
							Seasoning on Certified Sectors		
							Additional Sectors		
							Last Sector		

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