AIRSPACE STRUCTURE, FUTURE ATC SYSTEMS, AND CONTROLLER COMPLEXITY REDUCTION

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Abstract

Airspace structure is a key factor influencing controller cognitive complexity as it forms a basis for abstractions simplifying controller mental models of air traffic situations. In evaluating the feasibility of new Concepts of Operations (Con-Ops), it is important to consider the effects of changes to the structure of the system and its related impacts on controller cognitive complexity. Examples of key cognitive complexity considerations for future ATC systems are identified by examining three opportunities to modify airspace structure. A part task experiment was used to further investigate the impact of one of those opportunities on controller cognitive complexity, the introduction of time-based control. The hypothesis of structure's impact on controller complexity was supported through an innovative aircraft complexity assessment technique Benefits of time-based control were shown both in terms of controller performance and subjective complexity rating results.

Introduction

"Cognitive Complexity," or the cognitive difficulty of controlling an air traffic situation, is a limiting factor on the Air Traffic Control (ATC) system. Future ATC systems such as NextGen [1] are proposing new techniques and Concepts of Operations (Con-Ops). As a result, the role and task of human agents (e.g. controllers, pilots) will be changed; however, the cognitive complexity of controllers is expected to continue to be a major functional limitation on the capacity of Air Traffic Control (ATC) system.

The structure of the ATC system, or the physical and information elements that organize and arrange the ATC environment, is an important factor in controller cognitive complexity. Structure encompasses both physical objects, such as radio beacons, as well as information objects such as standard operating procedures and sector boundaries. Prior work [2] has described the important role of structure in helping controllers manage and reduce cognitive complexity. Structure shapes the air traffic controller's task and the cognitive strategies and mental models used to perform that task.

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. 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.

In order to identify key cognitive complexity considerations for future ATC systems, three examples of opportunities to improve the ATC system through structural changes enabled by new technologies are assessed. The analyses focus on illustrating how the understanding of structure and the use of structure-based abstractions to reduce complexity provide valuable insight into cognitive complexity benefits and challenges created by proposed changes to the airspace structure. A simulation experiment was performed to further evaluate the impact of possible future 4DT operational concepts on controller cognitive complexity..
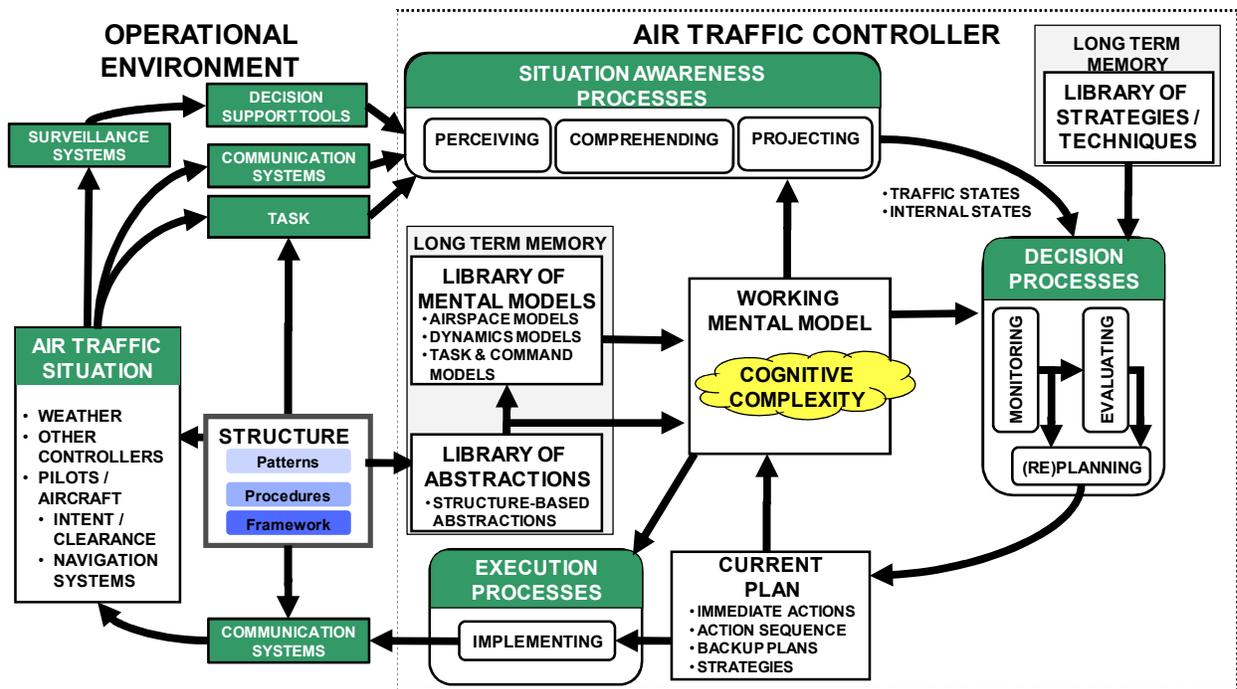
Figure 1. Cognitive Process Model

Background: Complexity, Structure, and Structure-Based Abstractions

Previous Work on ATC Complexity

Complexity in ATC has been a topic of significant research interest since the early 1960s [3]. In the mid 1990s, research efforts became focused on supporting the concept of dynamic density introduced as part of efforts towards "Free Flight" [4]. Multiple metrics of dynamic density have been proposed (e.g [3],[5],[6]). Some results have indicated that a unified version of the various dynamic density metrics may perform better than simple aircraft count [7].

The efforts to define dynamic density identified the importance of a wide range of potential complexity factors, including structural considerations. The resulting complexity metrics typically concentrated on only those factors that can be easily elicited from the geometry of an ATC situation ([8]). However, limiting considerations to only those easily elicited from the geometry of a situation may neglect important cognitive considerations that mitigate and help reduce complexity.

Cognitive Process Model

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 [2]. The approach included identifying key complexity factors, identifying core elements of structure, and developing hypotheses of the mechanisms by which structure influences controller cognitive complexity.

A combination of observational and analytic methods were used including:

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

The "in situ" observations and focused interviews were conducted during a series of site visits to both en-route and terminal ATC facilities in the United States, and Canada. Focused interviews were conducted with controllers and observations made of live operations. Traffic Management Unit (TMU) and training personnel were also interviewed. Additionally, representative traffic patterns were captured using data from the Enhanced Traffic Management System (ETMS). This tool allows

visualization of structural elements in the current system. It has also been used to generate illustrations of the use of that structure to reduce complexity.

Informed by observations made in the site visits and previous cognitive models in the literature, a cognitive process model was developed incorporating the key influences and effects of Structure (Figure 1). The cognitive 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. A more detailed description of the model can be found in [2]. In brief, the model integrates parts of Endsley's model of situation awareness [9] and Pawlak's identification of key types of decisions made by controllers: monitoring, evaluating and (re)planning [10].

At the center of the cognitive process model in Figure 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. The situation specific working mental model 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.

Figure 1 shows 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. Working mental models operate at a level of abstraction thought to be appropriate for the current cognitive activity. 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.

Structure-based Abstractions

Based on the observations, airspace structure was identified as an important factor in both sources of cognitive complexity and the strategies used to reduce cognitive complexity. The cognitive process model explicitly incorporates influences of structure on both the operational environment and controller cognitive processes. In the model Structure is shown both influencing the air traffic situation and its dynamics, the controller's task, and the communications used to implement commands modifying the air traffic situation. Through its impact on a controller's library of abstractions, Structure also plays an important role in simplifying controller working mental models.

Structure influences the working mental model by providing a basis for simplifying abstractions [2]. 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.

Based on the observations, 4 types of structure-based abstractions were identified (Figure 2):

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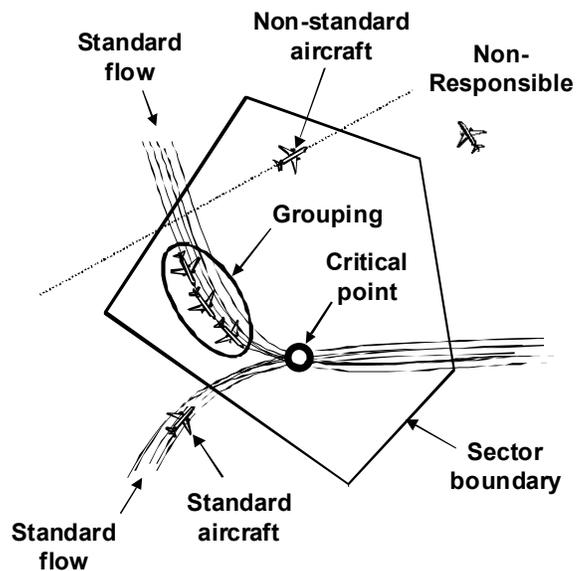- responsibility abstractions.

Figure 2. Illustration of examples of structure-based abstractions.

Detailed descriptions of each type of structure-based abstraction can be found in [2]. For example standard flow abstractions are internalizations of the standard flows of aircraft through and near a sector. 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 flow 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.

Structure-based abstractions are a key link between the influences of structure on the operational environment, and 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.

Identifying Cognitive Complexity Considerations in Future ATC Systems

Approach

In order to illustrate how key complexity considerations for future ATC ConOps can be identified, three examples of structural changes enabled by new technologies have been examined from the perspective of the cognitive process model shown in Figure 1. Examples assessed include optimizing existing route structures for flight-path efficiencies, multi-laning the existing route structure, and the introduction of 4-dimensional trajectories.

These opportunities 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. Nor are the results intended to be comprehensive; rather, they focus on illustrating how the cognitive process model and the use of structure-based abstractions provide valuable insight into cognitive complexity benefits and challenges created by proposed changes to the airspace structure. Both positive (reduced cognitive complexity) and challenging (potential for increased cognitive complexity) considerations are discussed.

In each example, a brief description is made of a performance shortfall of the current ATC system and one or more technical opportunities to address the shortfall. Examples of key cognitive complexity considerations are presented based on an analysis of the impacts of the opportunity on controller structure-based abstractions, the controller's task and the mechanisms available to the controller to control the air traffic situation (Figure 1).

Opportunity I: Optimized Route Structures

The growing recognition of environmental costs and increases in the cost of jet fuel is making the efficiency of aircraft trajectories increasingly important. The design of the route structure is a significant factor influencing the efficiency of aircraft trajectories. New technologies and operating concepts are providing more design flexibility and hence opportunities to optimize the route structure. New RNAV waypoints can be used to optimize and straighten existing airways and jet routes. 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.

Key cognitive complexity considerations were identified by examining the consequences of optimizing the route structure in the context of the cognitive process model. Optimizing the route structure through moving, modifying, and/or introducing new routes affects the patterns of aircraft behavior. In the context of the cognitive process model, the primary impact of these changes is on the dynamics of the air traffic situation with important consequences for controller abstractions.

Considerations from Impact on Dynamics and Abstractions

Optimizing the route structure provides several opportunities to reduce 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.

However, optimizing also introduces changes to the dynamics of the situation that potentially 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. For example, developing route structures that mix aircraft with different dynamics will create intra-flow interactions, potentially undermining the usefulness of a standard flow abstraction in the controller's working mental model.

Optimized route structures also have the potential to increase the number of critical points through shifts in the locations of flow crossings and merge points. 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 create the need for working mental models capable of supporting parallel evaluation and planning processes.

Optimized route structures 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 each critical point it passes through. 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.

Further Opportunities to Increase Efficiency

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.

Opportunity II: Multi-lane route structures

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. 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. Combined with reductions in separation standards, parallel lanes can be deployed within the confines of the existing route structure.[1]

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

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, and would provide a basis for a generalized standard flow abstraction of the collection of lanes.

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[1] 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 analysis was limited to opportunities to multi-lane existing uni-directional routes.

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.

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.

However, the impact of multi-laning on aircraft dynamics also creates potential complexity challenges. Multi-laning will likely increase the number of critical points in the airspace. This will occur if controllers model and track the crossing points between individual lanes and a crossing flow as distinct critical points. Furthermore, 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.

Considerations from Impact on Commands

Additional cognitive complexity considerations are identifiable by considering the impact of multi-laning on the commands used by controllers to manage and control a situation. The new multi-lane route structure can help reduce cognitive complexity by providing structural support for simpler resolution maneuvers. The presence of one or more parallel lanes would give 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, such as overtake situations, as the faster aircraft 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 also more difficult as there is no obvious structural basis to monitor conformance against.

Multi-laning also has the potential to negatively affect cognitive complexity by limiting the airspace available for resolutions and potential for standardized resolution maneuvers. In current "single lane" operations, airspace is typically available on at least one side of the track for resolution maneuvers.[2] The left image in Figure 3 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 3, 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. 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.

Additional Challenges

The discussion above highlights only some of the cognitive complexity challenges raised by introducing multi-lane route structures. Reduced separation standards between the lanes would require controllers to incorporate additional degrees-of-freedom into their working mental model in order to track the multiple separation standards, creating more complex working mental models.

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 procedures that remove responsibility for the relationships between aircraft within the multi-lane route structure from the controller. For example, 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.

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[2]   This is in addition to the potential for vertical resolution actions.
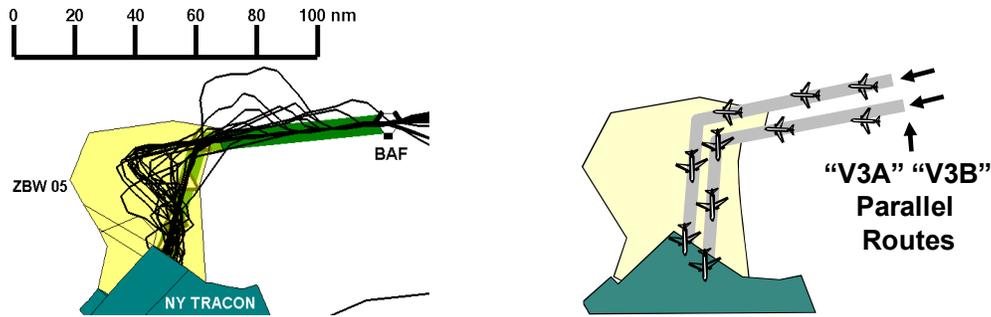
Figure 3. (Left) Examples of maneuvers (thin lines) to meet entry and exit constraints for traffic destined New York (NY) TRACON (heavy shading) through Boston Center sector 05 (ZBW 05 – light shading). (Right) Multi-lane routes block access to maneuvering airspace and create challenges for establishing standardized resolution maneuvers.

Delegating self-separation 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 aircraft as a single entity on the 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.

Opportunity III: 4D Trajectories

A final opportunity examined was the implementation of 4 dimensional (4D) trajectories. The shift to a 4D trajectory based system is anticipated to be a key aspect of next generation ATC systems [1]. 4DTs include controlled time-of-arrivals (CTAs) to one or more locations in an aircraft's clearance. 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. Guided by the cognitive process model in Figure 1, key cognitive complexity considerations

were identified by examining how the associated changes in the structure might affect controller abstractions, the dynamics, the task, and the commands available.

Cognitive Complexity Considerations from Impact on 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, 4DT operations also have the potential to create 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 4, 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.
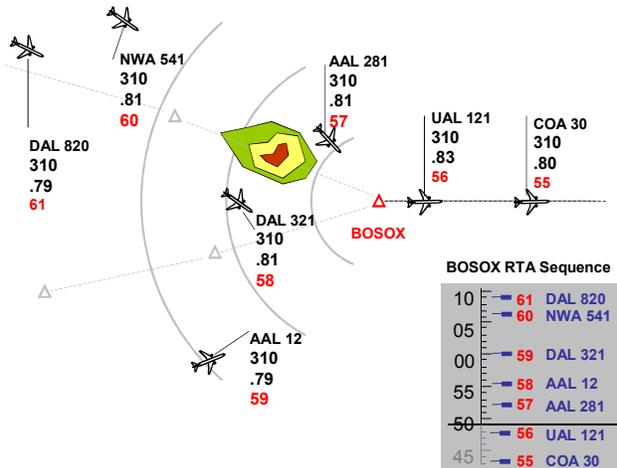
Figure 4. Example of a possible basis for time-based abstraction in a 4D trajectory environment.

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 CTA based abstractions 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, non co-located CTA points do not offer any direct reductions in the degrees-of-freedom in the working mental model.

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.

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. Aircraft maneuvering to conform to CTAs, or meet revised CTAs, fundamentally changes the dynamics of the situation by introducing uncontrolled and autonomous aircraft behaviors. In order to meet the assigned CTA, aircraft must be delegated the freedom to autonomously use one or more of speed changes, lateral maneuvers, and/or vertical maneuvers to adjust their trajectory. Delegating the freedom to maneuver also includes the timing of those maneuvers, further adding to the variability, and undermining the predictability of the situation. This introduces uncertainty into the dynamics as there are multiple different trajectories, each with unique dynamics, that are compatible with an assigned CTA, making it more challenging to model aircraft behavior.

Uncertainty in the dynamics makes it more difficult for a controller to accurately project the situation and use simplifying abstractions. However, the effects can be mitigated in part by standardizing the aircraft maneuvers used to meet a CTA. Restricting aircraft to maneuvering in a single degree of freedom (e.g. speed-only, or laterally only) would also simplify the dynamics for the controller.

4DTs also have the potential to create situations where a controller is 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 [11]. 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.

Impact on Commands

Additional cognitive complexity considerations, were identified by examining potential impacts of 4DTs on controller commands. The introduction of

time-based control mechanisms in 4DT operations will create 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). [3] 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.

Summary of Identified Cognitive Complexity Considerations

The cognitive process model and identification of structure-based abstractions provides a useful perspective for identifying key cognitive complexity considerations arising from changes to structure. Examples of key considerations include preserving the bases of existing abstractions, minimizing the order of the problem, or degrees-of-freedom required in a working mental model, limiting the number of and dependencies between critical points, and considering the impact on available resolution maneuvers and commands.

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, also reducing the order of the problem. 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 on commands. Commands

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[3] This is a similar effect to using altitude changes as resolution actions. A single command resolves the original conflict immediately and in a manner that definitively resolves the conflict.

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, and preserving airspace in order to support standard resolution actions, simplify planning.

Taking these considerations into account when developing future ConOps allows system designers to manipulate structure in ways that reduce cognitive complexity. This can help manage the risk of cognitive complexity considerations limiting the feasibility of the ConOps.

Experimental Study of 4D Trajectories

In order to further investigate the impact of 4D trajectories on controller cognitive complexity, a part-task simulation experiment was conducted. The experiment compared controller performance and complexity ratings between current operations and a simple version of 4D trajectories operation, time-based control at a metering fix. A human-in-the-loop fast-time simulation was developed in MATLAB to serve as the test bed for the experiment. In order to examine participant perceptions of complexity a new complexity probe technique was developed and applied in the experiment to explore individual aircraft's contribution to controller complexity.

Experiment Design
Scenario and Participants

The simulation modeled a generic arrival airspace with multiple merge points and was generally representative of one of the arrival flows to Boston. There were four major streams of arrival traffic and several crossing flights. One metering fix was included as the reference point for all arrival times. The traffic load varied with time and followed the same pattern in all scenarios; each run started with a low traffic level (12 ac/hr), increased to a high traffic level (18 ac/hr) in the middle, and decreased to a low traffic level (12 ac/hr) again at the end.

Twenty-two participants, all with either simulated or real air traffic control experiences, completed the experiment. One participant was an operational air traffic controller. Fourteen participants were upper year students majoring in Air Traffic Control (ATC) from Daniel Webster College. Eight participants were recruited from the Virtual Air

Traffic Simulation Network (VATSIM). Each participant completed six scenarios, experiencing each form of schedule for both time and space based control. Scenario orders were counter-balanced to address potential learning effects. All the participants had been trained in real-time radar control simulations in the CTI program.

Independent Variables

Control type and schedule type were the two independent variables in this experiment (Figure 5). Two different control types representing the current operation and a simple version of 4DT operation respectively were the primary research interests (see Figure 6). The baseline condition was a control type referred to as Position-Based Control, which represents current operation in which aircraft were controlled by vector and speed commands.

4DT condition was represented by a control type called Time-Based Control, in which aircraft can be controlled by time-of-arrival at a metering fix in addition to vector and speed commands. When a controlled time-of-arrival (CTA) command was given to an aircraft, the aircraft would adjust its speed automatically to meet the assigned time-of-arrival while continuing along its current route.

The additional functionality of controlling time-of-arrival in Time-Based Control was facilitated by the left side of the timeline display in the simulation (Figure 7). The participant could click on the timeline to give the CTA command. At all times either the assigned CTA or an estimated time-of-arrival (ETA) were shown on the left side of the timeline display. This functionality was not available in Position-Based Control.

Three types of schedule at metering fix were used in the experiment as a secondary independent variable, since the objective schedule will affect the system performance significantly. The three types of schedule included were None, FCFS and CPS. None means no schedule was displayed. FCFS and CPS are two kinds of optimized schedule. Details about the schedules can be found in [12].

Dependent Variables

The task of the participants was to direct arriving traffic to the metering fix in a safe and efficient manner. The tasks were prioritized in the following order: to maintain separation; to direct arrival traffic to the metering fix; to manage arrival

traffic to meet the schedule when a schedule is present; and to minimize travel time for arrival traffic when no schedule is present.
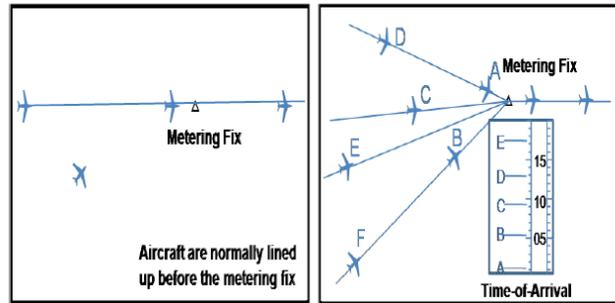

Figure 5. Design matrix

Figure 6. Control types: current operation (left) and 4DT operations (right):
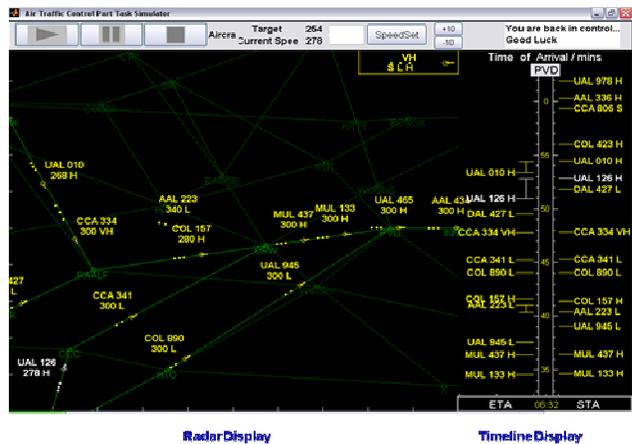

Figure 7. Main interface display.

Metrics of controllers' performance and perceived complexity were used to assess the impact on controller cognitive complexity. Controllers' performance was measured by conformance to the schedule (if present) and operational errors. The schedule conformance was calculated by the difference between actual arrival time and scheduled arrival time. The schedule conformance was included due to the potential requirement of time

conformance in NextGen environment to increase system capacity and efficiency. The operational errors were measured by the number of separation violations and aircraft exiting the airspace not through the metering fix area.

Controllers' perceived complexity was measured using a modified Air Traffic Workload Input Technique (ATWIT) [13]. The simulation was paused at five specified sample times and the perceived complexity was measured using a 7-point Likert scale to indicate the level of cognitive complexity experienced at that moment. At the same sample times, a new complexity probe method, was conducted.

Aircraft Complexity Assessment Method

A new complexity probe method, Aircraft Complexity Assessment, was used to assess the contribution of individual aircraft to complexity. No complexity probes used in the past have explicitly assessed each individual aircraft's contribution to cognitive complexity.

In this method, experiment participants were asked to identify specific aircraft that contribute higher complexity load to the overall complexity situation than a standard aircraft on the screen shots of a traffic situation. The standard aircraft was selected as an aircraft on a standard route without any potential conflicts. An example of the assessment results is shown in Figure 8.
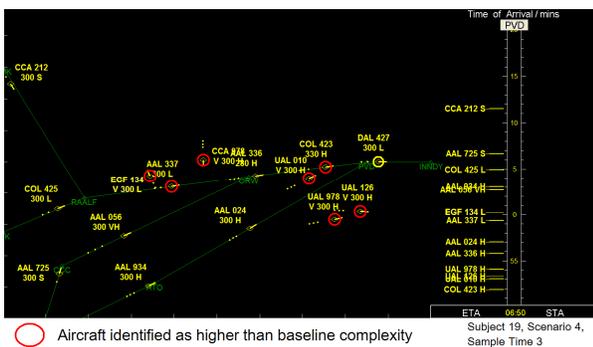

Figure 8. Example Aircraft Complexity Assessment result.

The Aircraft Complexity Assessment was conducted at the same time as the perceived complexity measurements during the run. It is acknowledged that this method had the disadvantage of interrupting ongoing controller tasks but provides

a direct way of assessing perceptions of aircraft complexity relative to the airspace structure.

Results

Schedule Conformance

Schedule conformance is expected to be an important performance consideration in future ATC system. Schedule conformance was determined by measuring the difference between actual arrival time and scheduled arrival time. As shown in Figure 9 schedule conformance was significantly improved in Time-Based Control than in Position-Based Control $(F(1; 48) = 4.86; p = .032)$.
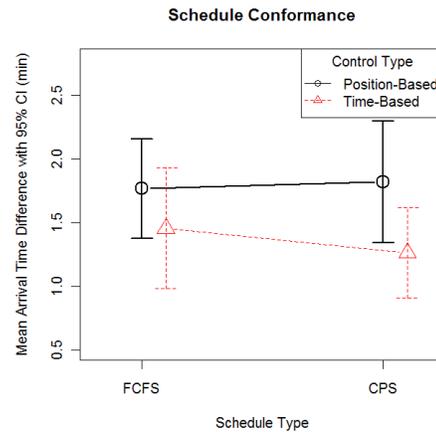

Figure 9. Schedule Conformance.

Operational Errors

Operational errors included separation violations and aircraft exiting the airspace not through the metering fix area. The frequency of operational errors in each condition is shown in Figure 10. ANOVA analysis showed that the difference in operational errors in Time-Based Control as compared to Position-Based Control was marginally significant $(F(1; 72) = 3.00; p = .088)$.
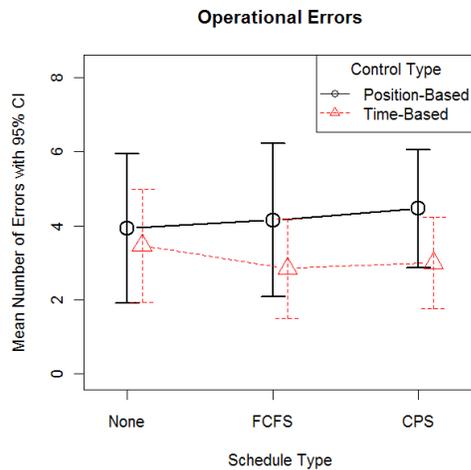
Operational Errors

Figure 10. Operational Errors.

Perceived Complexity

The results from participant perceived complexity ratings (Figure 11) showed that participants experienced a lower level of complexity in Time-Based Control than in Position-Based Control. Mann-Whitney test showed marginally significance (Z = -1.71; p = .087).
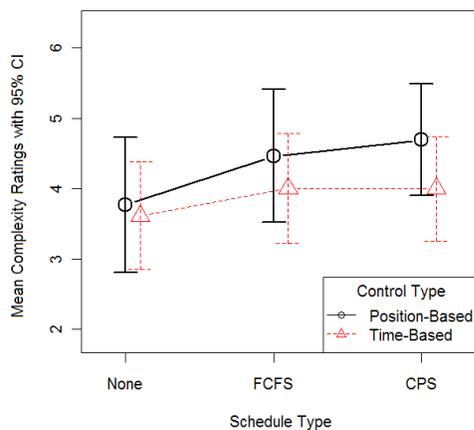

Figure 11. Perceived Complexity

Aircraft Complexity Assessment Analysis

The aircraft complexity assessment method provided insight into the impact of structure on controller complexity. The results supported the hypotheses on the use of structure in simplifying the cognitive complexity of air traffic control.

As shown in Figure 12, aircraft off the route structure were much more likely to be rated as high complexity than those on the route structure.

Whether an aircraft is on-route or off-route was determined based on the aircraft's position relative to the standard route structure (see Figure 8). A student t-test showed there was a significant difference in the percentage of high-complexity aircraft being on route or off-route($t(425) = 8:28$; $p < .001$). No significant difference was observed in this effect between position-based control and time-based control.
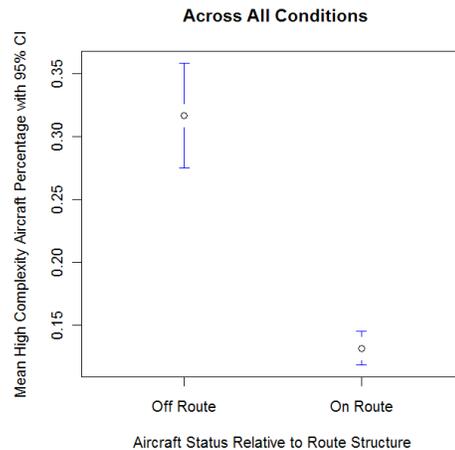

Figure 12. Aircraft Complexity Assessment results

This finding is consistent with and supports the hypothesis that the underlying structure-based abstractions facilitate the process of simplifying and understanding traffic pattern for experiment participants. When an airplane was off the standard route, it had a higher potential to be considered as an airplane contributing higher level of complexity.

Experiment Conclusion

The results in this experiment showed the simple version of 4DT operation enhanced controller performance and reduced perceived complexity. The indications from all the dependent variables were consistent in showing the benefits of Time-Based Control, although some of the results were marginally statistically significant. Better schedule conformance and lower error rate were found in Time-Based Control relative to Position-Based Control. Participants perceived lower complexity in Time-Based Control than in Position-Based Control.

Summary

The cognitive process model in Figure 1 incorporates multiple influences of structure, a key

factor in controller cognitive complexity. The examination of three opportunities to improve system performance, shows how it can be a useful tool for identifying key cognitive complexity considerations in future ATC ConOps.

The examination has identified several examples of key cognitive complexity considerations. 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.

Taking such considerations into account helps manage the risk of cognitive complexity considerations limiting the feasibility of the opportunity. New structures such as the transition to time-based control ConOps also present opportunities to introduce structure supporting new types of structure-based abstractions. The results of a part task simulation experiment comparing time based and position-based control showed significant benefits to 4D trajectories. Analysis of complexity ratings using a novel Aircraft Complexity Assessment probe reinforced the importance of understanding the role of structure on cognitive complexity in current and future ConOps.

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