USE OF STRUCTURE AS A BASIS FOR ABSTRACTION IN AIR TRAFFIC CONTROL

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The safety and efficiency of the air traffic control domain is highly dependent on the capabilities and limitations of its human controllers. Past research has indicated that structure provided by the airspace and procedures could aid in simplifying the controllers cognitive tasks. In this paper, observations, interviews, voice command data analyses, and radar analyses were conducted at and using data from the Boston Terminal Route Control (TRACON) facility to determine if there was evidence of controllers using structure to simplify their cognitive processes. The data suggest that controllers do use structure-based abstractions to simplify their cognitive processes, particularly the projection task. These structure-based abstractions were outlined and their effect on various ATC cognitive processes were discussed. Suggestions for the design of future ATC information tools were provided based on the findings from this study.

INTRODUCTION

Increasing the efficiency and the capacity of the air traffic control (ATC) system is an important goal that is currently limited by cognitive capabilities of the human controller. Controllers are required to maintain minimum separation between every aircraft within their airspace at all times. Pair-wise conflict comparisons can reach up to 105 individual comparisons between 15 aircraft (a normal upper limit) in the sector. These mental conflict probes must then occur every 30 seconds or so to ensure enough time to provide a conflict avoidance command to the conflicting pair. It is unlikely that controllers perform this pair-wise comparison in this manner, therefore it is critical to better understand the alternative cognitive organization that controllers have developed to perform this safety-critical task.

Let us first consider a proposed model of the ATC cognitive processes. Figure 1 depicts a functional model of the air traffic controller's primary cognitive tasks. This model has evolved using data from a series of ATC field studies performed by the International Center for Air Transportation (Reynolds, et al. 2002; Davison & Hansman, 2001; Histon, et al., 2001). Situation awareness and Decision processes portions of the model were adapted from Endsley (1995) and Pawlak (1996), respectively.

In this model, information is fed into the controller through **Perception**, primarily through the auditory and visual modalities. This information is then **Comprehended** in relation to the goal-relevant tasks of the controller. A **Projection** of the immediate future state of the system is then created using information from the environment that feeds experience-based mental models of the system entities. Gathering and using this information to project into the future was termed the Maintenance of Situation Awareness by Endsley (1995).

The projection created in the Situation Awareness portion is then **Monitored** against the controller's "Current Plan". If the projection is not entirely consistent with the "Current Plan", the future state of the system is then **Evaluated** with respect to the controller's threshold of acceptability. If the projected state of the system is in conflict with the set constraints, **Planning** is then used to generate an action that not only will return the projected state adequately within the boundaries, but that will also minimize the monitoring requirements imposed on the controller.

In the model, the **"Current Plan"** is generated by the controller's planning process and is greatly influenced by past experience. The "Current Plan" represents the controller's internal representation of a time-dependent 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.

The "Current Plan" then feeds the **Action Implementation** process, determining the time at which the controller commands the pilots, either through voice or through information tools (e.g., datalink).

One of the primary cognitive tasks in the functional ATC cognitive task model in which expertise reveals itself is in the **Projection** stage of *Situation*

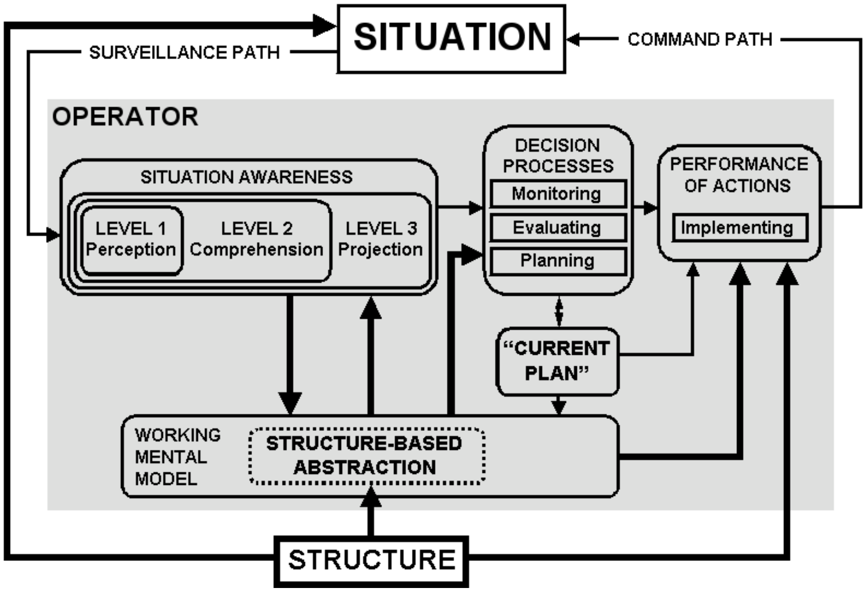

Figure 1: Generalized model of the influence of structure on the cognitive tasks of the air traffic controller.

Awareness. The controller's projection task is unique as compared to other domains due to the fact that controllers provide vector commands to the aircraft, thereby reducing the aircraft's intent uncertainty almost completely. As a controller develops experience, he or she builds up knowledge about how the "blips" on the radar screen behave and what information about the blip indicates to the controller a behavior specific to that blip.

Pieces of this expert knowledge are retrieved and integrated to form a "mental model" of the behavior of that blip. In this paper, the term "mental model" is defined as the controller's dynamic representation of the system integrated to respond to the needs of a particular projection task (Gentner & Stevens, 1983; Bainbridge, 1992; Wilson & Rutherford, 1989; Moray, 1998; Moray, 1987; Doyle & Ford, 1997). This mental model is then fed information from the environment providing a projection of the system state (Mogford, 1997).

As the controller develops experience in projection, the full extent of the information known about the system results in a model too complex to be used in real-time. An abstracted model is therefore used in real-time projections. Abstractions are a means of representing the essentials of the system dynamics in a cognitively compact format that is manageable within the constraints of human memory and processing. Rasmussen (1986) states that abstraction is "not merely the 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."

How extensively the system may be abstracted is partly dependent on the available resources of the controller, which fluctuates under different levels of workload (Athènes, et al., 2001; Sperandio, 1978). As the available resources (e.g., memory) become scarce, less diagnostic information is either abstracted out or it is forgotten completely (Bisseret, 1970).

While it is useful to consider *when* the mental model used by the controller is abstracted, it is just as critical to understand *how* this representation is abstracted. Recognizing how the controllers abstract the traffic situation cognitively is a critical step in understanding the basic requirements of decision support systems that are designed specifically to aid them in times of high workload.

From previous field studies in the air traffic control domain, it has been suggested that the air traffic control structure is a key component influencing how this abstraction process occurs (Reynolds, et. al, 2002; Histon, 2001). Structure is defined as a set of constraints (either physical or human-imposed) that limits the evolution of the dynamics of the system. Examples of physical structure include the ILS beam used during an instrument approach and the location of a mountain range during a sightseeing flight in the Rocky Mountains. Examples of human-imposed structure include airspace boundaries and flight levels. Each of these examples of structure establishes constraints such that, if penetrated, either physical or system laws will have been broken resulting in loss of life or significant reprimands. Thus, structure enables the controller to expect the aircraft to at least remain within the constraints under normal circumstances.

Key structure-based abstractions identified in previous work include *standard flows*, *groupings*, and *critical points*. (Reynolds, et. al, 2002; Histon, 2001) The *standard flows* abstraction emerges as a means of classifying aircraft into standard and non-standard classes on the basis of their membership in established flow patterns in a sector. An aircraft identified as a member of a standard flow carries with it an associated set of higher-level attributes such as expected future routing, ingress and egress points from the airspace, and locations of probable encounters.

A *grouping* abstraction was identified that linked aircraft by common properties for the purpose of reducing the overall complexity of the situation. An example of such a basis is the standard flight levels associated with particular directions of travel.

Critical points in the airspace were also identified as an example of a structure-based abstraction. The underlying structure, in the form of crossing and merge points of flows, will tend to concentrate the occurrences of encounters at common locations. Focusing on the intersection points of aircraft flows reduces the need for controllers to evaluate the potential for conflict over all possible pairs of aircraft within those flows.

Air traffic structure is not only established through environmental features and procedures established for the ATC system as a whole, but structure is also imposed on the traffic dynamically with each command given to the pilot. For example, once a controller has given the pilot an altitude command, the aircraft is expected to remain within +/- 300 feet of the commanded altitude.

This discussion of structure aligns itself with the principles of ecological psychology (Gibson, 1979; Vicente, 1999) that suggest expertise results from acquiring knowledge of goal-directed constraints present in the environment. Vicente & Wang (1998) provide empirical evidence in several domains (medical diagnosis, chess, process control) of the advantage that experts have over novices in seemingly random situations due solely to their knowledge of the structural constraints of the environment.

We have provided evidence suggesting that air traffic controllers are able to effectively abstract the useful pieces of a mental model to allow projection of the future behavior of the aircraft using structure. The controllers are also able to establish a dynamic structure through their commands to the pilots within their airspace. Theoretically, the controllers could provide additional structure that is not mandated in the air traffic control procedures or letters of agreement between facilities as a response to workload or to simplify their task. In this paper we investigate how the controller uses structure to simplify the projection task in the context of the Boston Terminal Radar Control (TRACON) ATC facility.

METHOD

To probe how air traffic controllers impose structure onto the traffic within the sector and how this structure simplifies the task of projection, four complementary approaches were taken.

Field observations at the Boston Terminal Radar Control (Boston TRACON) were conducted to understand whether controllers consciously use structure during their control. During the month of August 2002, 15 field observations were performed to gain insight into the operations of the Final Approach sector in the Boston TRACON. Notes were taken on methods controllers appeared to use to simplify their traffic situation. To better understand the field observations, Boston TRACON facility Standard Operating Procedures (SOPs) were reviewed to determine recommended procedures and facility constraints.

As patterns of behavior emerged from the observations (e.g., consistent speed commands), structured interviews were conducted with final approach controllers to investigate whether the patterns could be further substantiated. Interview questions consisted of the following:

- Are there standard altitude, airspeed, and heading commands that you give to aircraft entering through a particular fix? If so, what are the standard commands for the landing 4R/4L runway configuration?
- Do you partition aircraft into certain groups to simplify your control task? If so, what are the groups and in what circumstances do you use the groupings?

ATC final approach voice command data was also collected on September 25, 2002 and December 16 and 17, 2002. The total hours of voice command data analyzed was 13 hours, and this data revealed the commands during 8 controller shifts (it is possible that controllers could perform multiple shifts at final). Most of the data collected reflected the periods using the runway configuration landing runways 4R & 4L, therefore data was analyzed based on landing 4R & 4L procedures.

Radar data from the vicinity of the Boston TRACON was provided by MIT Lincoln Laboratories' ASR-9 radar for the days of December 16-17, 2002. Aircraft returning transponder code 1200 were filtered out due to the fact that these aircraft are not under ATC control. The radar returns were then inputted into MATLAB software and trajectories for the aircraft were generated linking common transponder codes.

RESULTS

The results retrieved during the study served two purposes: 1) to document the use of structure in the Boston TRACON through radar trajectory data and voice command analyses, and 2) to understand how this structure allowed the controller to cognitively simplify the air traffic situation through observations and interviews.

Radar Trajectory Data

The Boston TRACON controllers are provided with recommended procedures to use on arrivals and departures for each runway configuration through the Boston TRACON SOPs. In Figure 2, the recommended arrival procedure for landing runways 4R/4L configuration is illustrated. Arrivals are separated into jet and propeller groups. Jets are fed into the TRACON through fixes BRONC, SCUPP, and PVD. Propeller aircraft are fed into the TRACON through fixes BRONC, SCUPP, LWM VOR, WOONS, and FREDO.

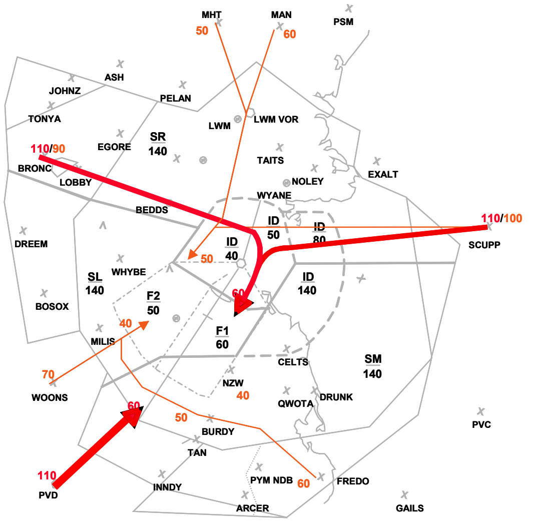

Figure 2: Arrival procedure outlined in Boston TRACON SOPs for landing 4R/4L runway configuration. Thick arrows are jets & thin arrows are propeller aircraft. (Courtesy of Boston TRACON Training)

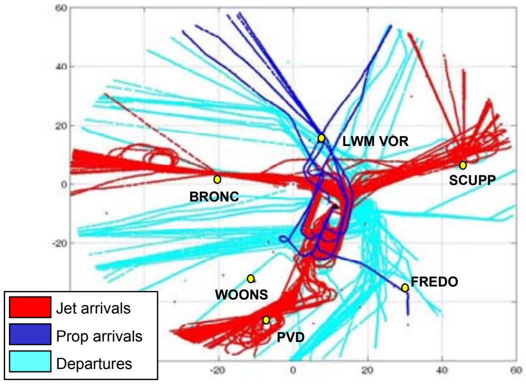

Figure 3: Radar trajectories for Boston TRACON arrivals and departures for December 16, 2002. (Radar data courtesy of MIT Lincoln Laboratories)

The radar data for arrivals and departures on December 16-17, 2002 are illustrated in Figure 3. Even though the controllers are not required to follow the SOP arrival and departure procedures,

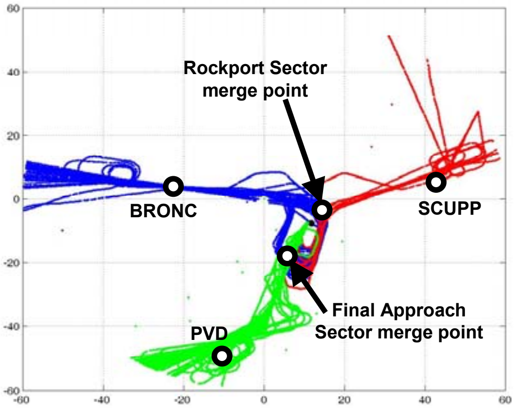

Figure 4: Boston TRACON jet arrival flows using landing 4L/4R configuration on December 16-17, 2002 illustrating critical points within the facility.

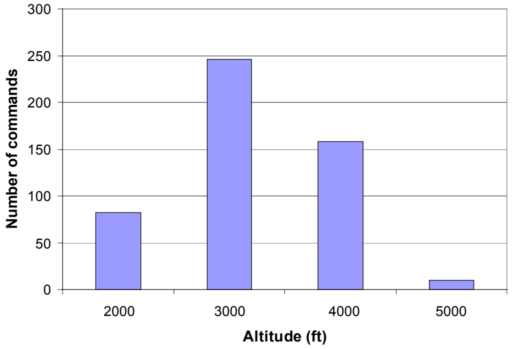

Figure 5: Altitude command frequency distribution for all aircraft through the Final Approach sector of the Boston TRACON on September 25, December 16 & 17, 2002.

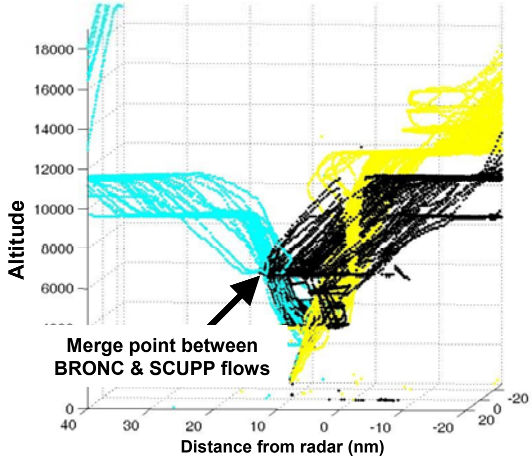

Figure 6: Altitude transitions of merging jet arrivals for Boston TRACON on December 16-17, 2002. (Radar data courtesy of MIT Lincoln Laboratories)

the radar data reveal that they do, for the most part, follow the SOP. The SOP provides the *standard flow* for the TRACON.

Critical points are also evident from the radar trajectory data. Figure 4 depicts only the jet arrival flows for December 16-17, 2002. Two merge points and three holding points demonstrate the areas in which much of the activity occurs within the Boston TRACON. The holding points are also the entry points for jets into the TRACON.

One particularly noticeable and consistent deviation from the SOP is apparent in Figure 4. The jet arrivals from BRONC sometimes proceed on a left-downwind approach instead of the right-downwind approach recommended by the SOP. Observations confirmed that this left-downwind approach was used only in cases of light traffic from the SCUPP direction, maintaining the two merging flows (rather than three) in the Final Approach sector.

Voice Command Analyses
To reveal if and how controllers apply additional structure at the command level, frequency distribution plots were generated using voice command data from the Final Approach sector.

The first analysis compiles data over 3 days and 8 controllers (for only the landing 4R/4L configuration). The altitude distribution in Figure 5 suggests that controllers are discretizing altitude commands in even thousands. This correlates with the observation data in which it was discovered that to provide separation with little demand on monitoring resources, the controllers separated laterally merging flows through altitude until they were required to capture the ILS. Figure 6 illustrates the concept of separating merging flows by altitude until they are laterally merged. The black flow on the right are the jet arrivals from BRONC fix, while the flow from the left are the jet arrivals from SCUPP. As they merge to the point indicated, the SCUPP flow is kept at 9500 ft while the BRONC flow is descended to 5500 ft. The vertical separation requirement between aircraft in the TRACON is also 1000 ft, contributing to the discretization.

The total airspeed frequency distribution in Figure 7 indicates that 170 kts was the primary

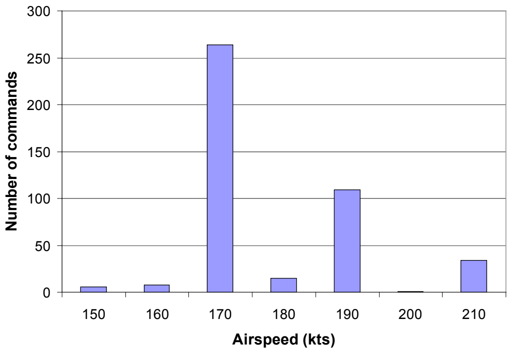

Figure 7: Airspeed command frequency distribution for all aircraft through the Final Approach sector of the Boston TRACON on September 25, December 16 & 17, 2002.

airspeed command given to the aircraft on approach. This, too correlated with the observations, in which it appeared that controllers in the final approach sector would try to keep all aircraft in the sector progressing at the same airspeed unless they were trying to make or fill in a "hole" in the aircraft line-up.

Finally, aircraft 1st and 2nd command types were analyzed to determine what axis the final approach controller found most important to apply some sort of structure. The command type distribution for the 1st and 2nd aircraft voice commands is illustrated in Figure 7. The most frequent first command given to aircraft is a command in the vertical axis. This is a reasonable expectation since altitude separation is used as a robust means of separation assurance.

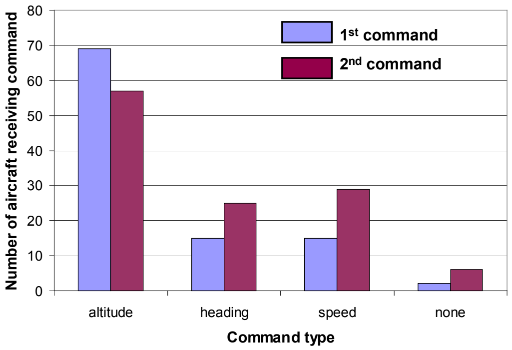

Figure 7: Command type frequency distribution for the 1st and 2nd command types that all aircraft received upon entering Boston TRACON Final Approach sector on September 25 and December 16-17, 2002.

Field Observations & Interviews

In the field observations and interviews, controller operations were studied and controllers were verbally probed to determine how structure is used to simplify their projection tasks. It was observed that controllers use the SOP arrival and departure routes as a template for the nominal routes through the TRACON. These routes meet all constraints, so it is simpler to adhere to these routes. One controller stated that deviating from the SOP routes created a "snowball effect" that required coordination with other controllers to avoid constraints that the new route breaks.

During observations, controllers also appeared to be assigning a default airspeed to aircraft entering the sector. When controllers were questioned in regard to this practice, 3 separate controller concurred that there was a "default airspeed" depending on the runway configuration. The controllers stated that they vary from this speed to either "close the holes" in the arrival traffic line-up or to "create holes" for aircraft from other flows. This airspeed perturbation method is particularly useful with traffic flows involving no major turns (e.g., the PVD jet arrival flow in Figure 4).

Often the controllers' tasks were driven by traffic restrictions imposed by other sectors and facilities. These included restrictions such as "miles-in-trail" restriction that requires aircraft to be a certain number of miles separated from the next aircraft at an ingress point to another facility. Because of traffic restrictions, controllers project longitudinal separation along the arrival or departure routes to ensure that the separation at the ingress point will meet the restriction.

The controllers also appeared to be grouping the traffic in several ways depending on the particular task. Across TRACON controllers, aircraft were grouped with traffic flows, determined mostly by their arrival and destination.

Because the Final Approach sector requires highly accurate projections due to the nature of vectoring aircraft to the ILS, understanding fine behavior differences between aircraft becomes a key element to a successful projection. Controllers stated that transition behaviors of aircraft are particularly important to the departure projection task.

Controllers also group traffic into type of aircraft (e.g., old jet, new jet, and propeller). This grouping is useful when performing several control tasks. On final approach, the type of aircraft can determine how fast the aircraft is able to fly, which is useful for the purposes of making or filling in "holes" in the approach line-up. Propeller aircraft are not capable of the same airspeeds as jets, which prevent them from closing a gap between them and a jet aircraft already flying at a high speed. It is useful to differentiate an "old" jet such as a Boeing 727 from a "new" jet such as a Boeing 767 on final approach because an old jet has slower descent behavior than a new jet.

Controllers responded that aircraft may be differentiated on the basis of airline during departures. Some airlines have departure procedures that affect at what altitude the aircraft will begin to end their climb. This behavioral pattern is used by the controller to make decisions about altitude and airspeed vectors to give subsequent aircraft to maintain minimum separation requirements on departure.

DISCUSSION

The data from this study suggests that structure does play a role in simplifying the controller's cognitive projection task. It is hypothesized that structure simplifies the projection task by reducing the lateral dimension of the aircraft's intended trajectory and linearizing the time/space dynamics of the aircraft relative to one another.

The SOP arrival and departure routes provide a lateral path that all aircraft arriving from and proceeding towards a particular direction follow. Therefore, if the controller must identify the intended lateral direction of an aircraft, the controller need know only the location of the aircraft to project the aircraft laterally. Evidence that controllers primarily rely on the SOPs for arrival routings is provided in Figures 2 & 3. Altitude can be a additional indicator of the intended trajectory, however the vertical dimension is generally reserved for robust separation assurance between traffic in the TRACON, as was shown in Figure 6.

Once the aircraft have joined the standard flows, the controller's projection is then only hindered by the problem of determining how fast each aircraft is proceeding along the lateral path. One way structure was found to simplify this aspect of the projection task was through establishing a limited number of critical points in the controller's sector. Figure 5 illustrated several critical points throughout the facility. The SOPs created 1-2 points in each sector to which all projections are made. The establishment of these points simplifies projection because the controller only needs to project the aircraft to 1 or 2 points rather than to an infinite amount required through the pair-wise comparisons of aircraft on random routes.

The time dimension of the projection task is also aided by the controllers' establishment of a default airspeed for aircraft within the sector. If all of the aircraft in the sector are progressing along standard lateral routes at the same speed, the aircraft are each moving the same distance with each update of the radar screen. Standardizing the speeds across aircraft, as was demonstrated through voice command data in Figure 7, equalizes the monitoring requirements across all of the aircraft.

The data from this study establishes the use of structured methods to control aircraft and provides controller input about how these structured methods aid in the projection task. An experimental scenario is now required to test these hypotheses to discover whether the presence of structure actually improves the controller's ability to project the future behavior of aircraft.

Two complementary experiments would allow thorough investigation of the benefits of structure to the control task. In Experiment 1, the controller would monitor an ATC final approach scenario for minimum separation violations and respond verbally if a violation is detected. The independent variables in this experiment would be the presence of structure (through procedures followed by the traffic monitored) and the level of traffic (high: 8-15 aircraft and low: 1-7 aircraft). The level of procedural structure followed by the traffic could be manipulated as well (e.g., heading only, heading and altitude, heading, airspeed, and altitude, etc.). The dependent variables to be measured could be time between response to conflict and actual conflict, false alarm responses, missed responses, and subjective workload. If structure truly aids the projection task, there should be increased reported workload, an increase in false alarms and missed detections, and decrease in time between response to conflict and actual conflict as structure is removed from the scenarios. This experiment is particularly valuable because of its ability to isolate the projection task, but it removes the option of the controller imposing his own structure that exists in the world.

Experiment 2 requires the controller to perform a final approach air traffic control task. The independent variables would be the amount of structure (both that the traffic follow and that the controller must adhere to), the dimensions that the controller is allowed to use to control the aircraft (e.g., heading only, heading and altitude, etc.) and the amount of traffic that the controller is required to control. The dependent variables in this experiment would be loss of separation events, subjective workload ratings, traffic throughput measurements, and subjective assessment of the strategies used by the controller during unstructured control task. This experiment complements Experiment 1 because it does not entirely isolate the projection task from planning & implementation, but it does provide a consistent task with the actual ATC task.

Understanding if and how structure benefits the controllers' projection task is critical in designing future air traffic control procedures and decision support tools. Consideration should be given to future technologies and concepts proposing to alter or remove this structure (e.g., free flight). Opportunities also exist to utilize structure's ability to simplify projection to improve the training regimes in ATC, to design airspace to be consistent with the controller's cognitive processes, and to improve the acceptance of new ATC information tools.

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REFERENCES

Athénes, S., Averty, P., Puechmorel, S., Delahaye, D., & Collet, C.,. (2002). "ATC complexity and controller workload: Trying to bridge the gap." *Proceedings of the International Conference on HCI in Aeronautics*, Cambridge, 56-60.

Bainbridge, L. (1992). "Mental models in cognitive skill: The example of industrial process operation." http://www.bainbrdg.demon.co.uk/Papers/MM.html

Bisseret, A. (1970). Mémoire opérationelle et structure du travail. Bulletin de Psychologie, XXIV, 280-294. English summary in Ergonomics, 1971, 14, 565-570.

Davison, H. J. & Hansman, R. J. (2001). "Identification of communication and coordination issues in the U. S. Air Traffic Control System," International Center for Air Transportation Report ICAT-2001-2.

Doyle, J. K. & Ford, D. N. (1998). "Mental models concepts for system dynamics research." *System Dynamics Review*, *4*(1), 3-29.

Endsley, M.(1995). "Toward a theory of situation awareness in dynamic systems." *Human Factors*, 37(1), 32-64.

Gentner, D. & Stevens, A. L. (1983). *Mental Models.* L. Erlbaum Associates: Hillsdale, N. J.

Gibson, J. J. (1979). *The Ecological Approach to Visual Perception.* Houghton-Mifflin: Boston.

Histon, J. M., Hansman, R. J., Aigoin, G., Delahaye, D. & Puechmorel, S. (2001). "Introducing Structural Considerations into Complexity Metrics", *4th USA/Europe Air Traffic Management R&D Seminar* (Orlando), (Reproduced in ATC Quarterly, June 2002)

Mogford, R. H. (1997). "Mental models and situation awareness in air traffic control." *International Journal of Aviation Psychology*, *7*(4), 1997.

Moray, N. (1998). "Identifying mental models of complex human-machine systems." *International Journal of Industrial Ergonomics, 22*, 293-297.

Moray, N. (1987). "Intelligent aids, mental models, and the theory of machines." *International Journal of Man-Machine Studies, 27,* 619-629.

Pawlak, W. S., Brinton, C. R., Crouch, K., & Lancaster, K. M., (1996). "A framework for the evaluation of air traffic control complexity." *Proceedings of the AIAA Guidance, Navigation, and Control Conference*, San Diego.

Rasmussen, J. (1986). Information Processing and Human-Machine Interaction: An Approach to Cognitive Engineering. Elsevier Science Publishing Co., Inc., Amsterdam.

Reynolds, T. G., Histon, J. M., Davison, H. J., & Hansman, R. J. (2002). "Structure, intent, & conformance monitoring in ATC", *Proceedings of the Air Traffic Management Conference*, Capri, Italia.

Sperandio, J. (1978). "The regulation of working methods as a function of workload among air traffic controllers." *Ergonomics, 21*(3), 195-202.

Vicente, K. J. (1999). *Cognitive Work Analysis: Toward Safe, Productive, and Healthy Computer-Based Work.* L. Erlbaum & Assoc.: Mahwah, N. J.

Vicente, K. J. & Wang, J. H. (1998). "An ecological theory of expertise effects in memory recall." *Psychological Review, 105*(1), 33-57.

Wilson, J. R., & Rutherford, A. (1989). "Mental models: Theory and application in human factors." *Human Factors*, *31*(6), 617-634.