COMPLEXITY MITIGATION THROUGH AIRSPACE STRUCTURE

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Cognitive complexity is a term that appears frequently in air traffic control research literature, yet there has not been a significant distinction between different components of complexity, such as environmental, organizational, and display complexity, all which influence cognitive complexity. It is not well understood if and how these different sources of complexity add to controller cognitive complexity and workload. In order to address this need for complexity decomposition and deconstruction, an experiment was conducted to explore whether or not different components of complexity could be effectively measured and compared. The goal of the experiment was to quantify whether or not structure in airspace sector design, in combination with changes in the external airspace environment, added to or mitigated perceived complexity measured through performance. The results demonstrate that for a representative ATC task, the dynamic environment complexity source was a significant contributor to performance, causing lower performance scores. There was no apparent effect, either positive or negative, from increasing airspace structure represented through a display.

INTRODUCTION

Addressing the difference between environmental and innate human complexity (often referred to as cognitive complexity), Herb Simon describes an ant's path as it navigates across a beach. The ant eventually reaches its destination, but because the ant must constantly adapt its course as a result of obstacles, the path seems irregular, laborious, and inefficient. Simon points out that while the ant's path seems complex, the ant's behavior is relatively simple as compared to the complexity of the environment. Simon proposes the following hypothesis as a result, "Human beings, viewed as behaving systems, are quite simple. The apparent complexity of our behavior over time is largely a reflection of the complexity of the environment in which we find ourselves (Simon, 1981, p. 53)."

This distinction between innate or cognitive complexity and environmental complexity is especially relevant considering the considerable research conducted in air traffic controller cognitive complexity. Several studies have investigated air traffic control (ATC) information complexity issues (see Hilburn, 2004; Majumdar & Ochieng, 2002) for a review). In this literature, several common complexity factors have emerged to include traffic density, traffic mix, aircraft speeds, sector size, and transitioning aircraft. These factors are asserted to affect cognitive complexity. However, in light of Simon's ant parable, these factors really represent environmental complexity factors that influence cognitive complexity. This is an important distinction because as can be seen in Figure 1, there are several levels of complexity that can affect an individual's cognitive complexity level.

Figure 1 illustrates the decomposition of "complexity" as it applies to human supervisory control systems. Human supervisory control (HSC) occurs when a human operator intermittently interacts with an automated system, receiving feedback from and providing commands to a controlled process or task environment (Sheridan, 1992). In complex HSC systems, in general two layers of interventions, organizational and display design can exist to mitigate environmental complexity, and thus reduce cognitive complexity. Organizational interventions include goals, policies, and procedures such as separation standards, checklists, airspace structure, etc. For example, many airspace sectors are designed to promote predominant

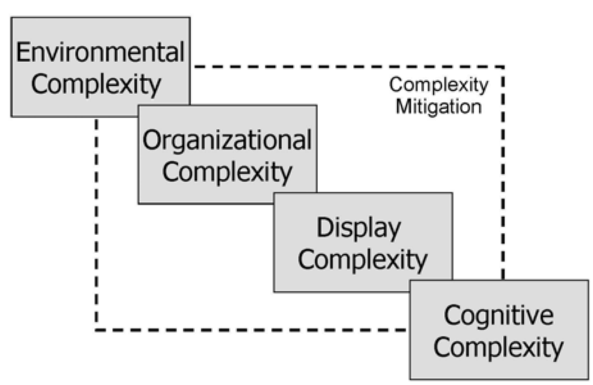

Figure 1: Human Supervisory Control Complexity Chain

traffic flows. Thus the design and the associated rules and procedures for control mitigate environmental complexity caused by increasing numbers of planes. However, when airspace becomes obstructed and saturated due to weather, congestion, etc., the need to follow procedures and sector limitations can over-constrain a problem, thus increasing the perceived complexity by the controller.

Displays are another example of intended complexity mitigation which could inadvertently add to complexity instead of reducing it. For air traffic controllers and in general all HSC operators, displays are critical in representing the environment so that a correct mental model can be formed and correct interactions can take place (Woods, 1991). In effect, to mitigate complexity, displays should reduce workload through transforming high-workload cognitive tasks such as mental computations into lower workload tasks through direct perception, i.e. visually (Miller, 2000). However, in complex and dynamic HSC domains such as ATC, it is not always clear whether a decision support interface actually alleviates or contributes to the problem of complexity.

COMPLEXITY AND STRUCTURE

In addition to traffic density and related factors, it has also been hypothesized that the underlying airspace structure is a critical complexity factor (Histon et al., 2002). In theory, airspace structure provides the basis for mental abstractions which allows controllers to reduce complexity and maintain situation awareness. Histon et. al., (2002) propose that these mental abstractions, known as structured-based abstractions, can be generalized to standard flows (reminiscent of Pawlak's (1996) "streams"), groupings, and critical points. Providing air traffic controllers with these interventions, either explicitly through design or implicitly through policy, should help controllers improve through mental models, reduce overall complexity, as well as reduce perceived workload.

In a study investigating judgment and complexity, Kirwan et al., (2001) determined that airspace sector design was only second to traffic volume, in terms of contributing to cognitive complexity. In terms of the model in Figure 1, airspace sector design straddles both the organizational and display complexity categories. Designed by humans to mitigate environmental complexity, airspace structure is an organizational policy. However, airspace structure contains significant visual components represented in displays, thus it is an environmental complexity intervention both from an organizational and display perspective.

Including interventions in airspace sector design such as critical points (points through which aircraft must pass) and designated standard flows (such as jet ways) can increase order and improve predictability, and thus lower cognitive complexity. However, it is also possible that when uncertainty levels increase, usually as a function of dynamic environmental factors such as changes in weather and available airspace, these same airspace structures could actually add to complexity since a controller's mental model of the airspace design must be adapted to the new conditions. Airspace structure and procedures mitigate complexity in what are termed "nominal" situations, but when an "off-nominal" condition occurs, such as an emergency or unexpected weather phenomena, the resultant increasing uncertainty causes complexity to grow (Athenes, Averty, Puechmorel, Delahaye, & Collet, 2002).

While other research has attempted to quantify the individual elements of complexity as a function of traffic flow (Masalonis, Callaham, & Wanke, 2003), little attention has been directed towards understanding the different sources of complexity such as depicted in Figure 1. In addition it is not clear if and how these different sources of complexity add to controller cognitive complexity. In order to address this need for complexity decomposition and deconstruction, an experiment was conducted to explore whether or not elements of complexity as depicted in Figure 1 could be effectively measured and compared.

METHOD

Apparatus, Participants, and Procedure

To objectively investigate the impact of environmental and structural complexity factors on controller performance, a human-in-the-loop simulation test bed was programmed in MATLAB® (Figures 2 & 3). Since the subject pool consisted primarily of college students, it was necessary to devise a simplified and abstract task that addressed the aforementioned complexity concerns, but still represented fundamental elements of ATC. In a simplified en route task, subject controllers were assigned a single sector, and were only required to provide heading commands to aircraft, while velocities and altitudes were held constant.

Twenty egress areas were located in the periphery of the sector, and each incoming aircraft was assigned a specific egress point. The primary goal was to direct the aircraft (a/c) to the assigned egress, and when an aircraft exited correctly, a score was generated. To provide an incentive for flying through a pre-determined sequence of waypoints (representative of a flight plan), subjects could collect additional points by directing their a/c through these waypoints. The number of points that could be won at every waypoint was displayed. To discourage controllers from directing aircraft through unnecessary waypoints just to gain points, scores were penalized based on an aircraft's total time of presence in the airspace sector beyond that expected for the optimal pre-determined path. A final component of the overall score was the penalty for flying through a no-fly-zone. No-fly zones represented constrained ATC airspace such as thunderstorms, military operating areas, and prohibited areas. Example waypoints, optimal paths for particular ingress and egress points, and no-fly zones are represented in Figure 2. Maximization of total score was the subjects' goal, and their total score was displayed in real-time.

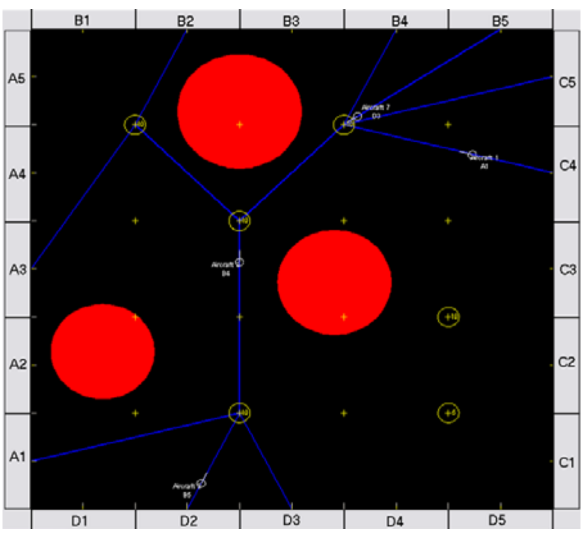

Figure 2: Interface with optimal paths shown

Training and testing were conducted using a Dell personal computer with a 21-inch color monitor, 16-bit high color resolution, and a 3.0GHz Pentium 4 processor. During testing, all user responses were recorded in separate files specific to each subject and scenario. A Visual Basic script was then written that scored and compiled the data into a single spreadsheet file for the subsequent statistical analysis. After signing required consent forms, subjects completed a tutorial that discussed the nature of the experiment, explained the context and use of the interface, and gave them the opportunity to understand the scoring mechanism. Subjects completed four practice scenarios that exposed them to every combination of independent variables. They then began the randomly ordered four test sessions, which also lasted until all aircraft had exited the airspace (approximately 6-7 minutes).

Experimental Design

Two independent variables were investigated. The first independent variable was the presence of structure, as displayed through the lines of maximum score (named "displayed structure"). As can be seen in Figure 2, in certain scenarios subjects were given structure through the display of the optimum paths (those that maximized the score as a function of waypoints and time). In the counter condition, subjects were given the waypoints (along with the number of available points), but were not shown the optimal path (Figure 3).

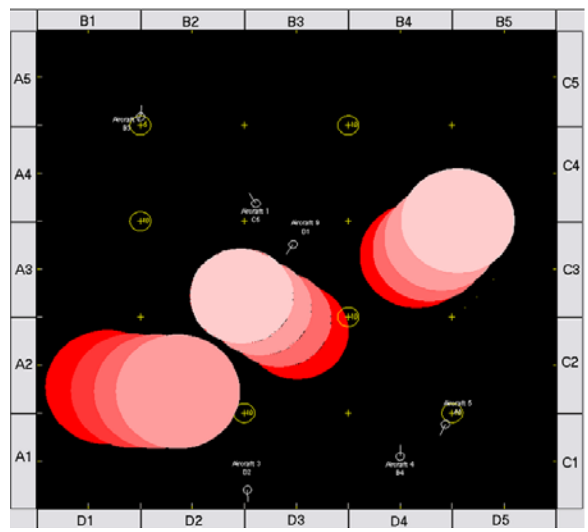

Figure 3: Interface with dynamic no-fly-zones

The second independent variable was the condition of the environment in terms of either static or dynamic no-fly-zones. In the dynamic condition, the no-fly-zones moved at rates of about two-fifths the aircraft velocity (figure 3), and representing changes in constrained airspace that often occur such as weather fronts and special-use airspace. It is important to note that the displayed lines were the optimum, but only in cases where they were not obstructed. In the dynamic condition, the dynamic no-fly zones cases would sometimes cover the paths, and thus the controller had to mentally regenerate new optimal paths. The motivation was to investigate whether or not such visual structure in an airspace sector, in combination with changes in the external airspace environment, added to or mitigated perceived complexity measured through performance.

A single dependent variable of total performance score was used. As described previously, the score was a linear and weighted function of aircraft egress correctness, bonus waypoints with penalties for no-fly-zone violations, and total time transitioning in sector. In the case of egress score, subjects received maximum points by directing their a/c to exit near the center of the egress, but did not receive points for exiting through the wrong egress. The egress scores decreased linearly from the center to the marked edges of the egress blocks. To maintain consistent scenario level of difficulty in order to minimize any learning effect, the four experimental scenarios were ninety degree rotations of each other. The statistical model used was a 2x2 fully crossed ANOVA and the four scenarios were randomly presented to a total of 20 subjects.

RESULTS AND DISCUSSION

The 2x2 ANOVA linear model (with and without displayed structure and dynamic vs. static environment) revealed that for the performance dependent variable, the environment factor was significant ($F(1,74) = 54.55$), $p < .001$, all $\alpha < .05$). The displayed structure factor and the environment*displayed structure interaction were not significant. Figure 4 depicts the average performance scores across all four conditions. It can be seen on inspection that the performance scores were clearly higher in the static environment scenario as opposed to the dynamic environment phase. Whether subjects had less or more displayed airspace structure did not significantly affect their scores. These results demonstrate that for this representative ATC task, the environmental complexity factor was a significant contributor to performance, causing lower performance scores. There was no apparent effect, either positive or negative, from increasing airspace structure.

In terms of the model in Figure 1, this experiment demonstrated for this representative ATC task, the main component of complexity associated with controller workload was environment, and not organizational or display-related. Dynamically changing airspace structure was far more influential than the design of the airspace itself. Thus while sector design may be a contributing factor to air traffic controller performance, environmental complexity factors such as thunderstorms and special use airspace that intermittently becomes available, are significantly larger contributors to individual cognitive complexity.

These results provide quantitative support for previous subjective assessments of controllers that active special use airspace increases complexity and would benefit from some display intervention (Ahlstrom, Rubinstein, Siegel, Mogford, & Manning, 2001). In light of the results reported here, it is likely that special use airspace (SUA), an organizational constraint, can increase complexity for controllers not because of the actual structure of the airspace, because the status can change. When SUAs cycle between active and inactive, especially relatively rapidly, environmental complexity increases, and could negatively affect controller performance. Thus a by-product of an organizational policy could be increased complexity on the part of controllers.

These results indicate that the development of decision support tools to aid controllers in SUA management is an area of research that deserves more attention Because of the temporal and cyclic nature of SUA, possible design interventions could include some kind of timeline display for SUA scheduling as well as intelligent decision support agents that can predict in advance when airspace could become available or deactivated.

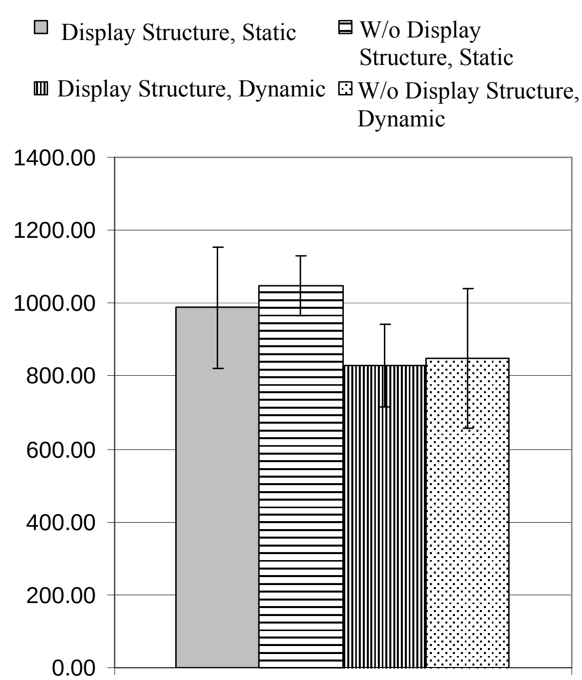

Figure 4: Condition Mean Performance Times

CONCLUSION

Complexity as it applies to the air traffic control environment cannot be simply categorized as "cognitive complexity," as there are different components of complexity, which are demonstrated in Figure 1. These components of environmental, organizational, and display complexity may not contribute in a linear and consistent manner to either cognitive complexity or performance. This study attempted to decompose two sources of complexity, an environmental factor caused by changing airspace, and an organizational/display factor caused by airspace design. Results show that the environmental complexity source of changing airspace was far more significant in influencing overall controller performance. These results support air traffic controllers' subjective opinions that special use airspace is a source of complexity (Ahlstrom et al., 2001), and that more work is needed for better display representation.

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