

# Deconstructing Complexity in Air Traffic Control

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While previous research has addressed controller workload as a function of cognitive complexity due to environmental and to a lesser degree, organizational factors, significantly less attention has been paid to the role of displays and complexity in the ATC environment. One drawback to new display technology is that in dynamic human supervisory control domains, it is not always clear whether a decision support interface actually alleviates or contributes to the problem of complexity. In an attempt to quantify the influence of environmental and display complexity factors on cognitive complexity, an experiment was conducted to determine if these two components could be effectively measured. Results revealed that the environmental factor of increasing aircraft number affected subject performance only slightly more than the display complexity factor of increased color categories. These findings are important because the use of color in displays is meant to reduce environmental complexity, not add to it.

## INTRODUCTION

The impact of complexity on air traffic controller workload has received considerable attention in recent years. 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, separation standards, aircraft speeds, sector size, and transitioning aircraft. In the literature these factors are asserted to affect “cognitive complexity”, the perceived level of complexity at the individual cognitive level. However, they also 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. Cognitive complexity is actually the lowest form of complexity in this model which can be affected by some or all of the preceding levels. Environmental complexity, for example, number of aircraft, weather, congestion, etc., contains environmental factors that in theory are mitigated by organizational intervention as well as displays. Goals, policies, and procedures are organizational elements, which in general exist to mitigate environmental complexity, but in fact, can add to cognitive complexity. For example, separation standards exist to mitigate complexity for controllers (and promote safety), however, when airspace becomes saturated, the need to maintain these organization-driven constraints causes situation complexity, and thus workload, to increase.

While previous research has been critical in addressing controller workload as a function of cognitive complexity due to environmental and to a lesser degree, organizational factors, significantly less attention has been paid to the role of displays in either adding to or mitigating

complexity in the ATC environment. One drawback to new display technology is that in complex and dynamic human supervisory control domains such as ATC, it is not always clear whether a decision support interface actually alleviates or contributes to the problem of complexity. In an attempt to separate and quantify the influence of environmental and display complexity factors on cognitive complexity, an experiment was conducted to determine if these two components could be effectively measured.

## DISPLAY COMPLEXITY AND COLOR

With advanced display technologies that allow designers to use hundreds of color conventions with no added system cost, there has been a recent increase in the amount of color used in ATC displays. However, there has been little, if any, consideration of how much color might be too much from an information processing perspective. Xing and Schroeder (in review) have documented the extensive

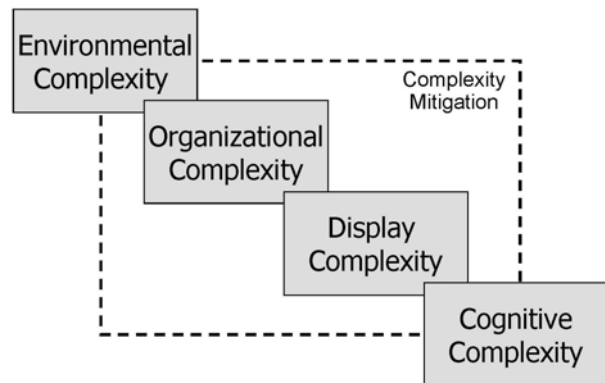


Figure 1: Human Supervisory Control Complexity Chain

and inconsistent color use in ATC displays.

Despite the improvements in search and organization tasks color can provide, previous research has shown that while subjects believed that color improved their performance, color did not improve target detection or identification (Jeffrey & Beck, 1972). In addition, the use of color can cause cognitive tunneling or “inattention blindness (Simons, 2000)”, in which operators may miss other important information on a display because they fixate on the more salient color change. Another possible problem with the current use of color in ATC displays is that many displays use the same color to identify different types of information, such as using blue to indicate both an airline type as well as a particular phase of flight. As the number of display colors increases, with possible multiple meanings, both the perceptual and cognitive load of controllers is increased, subsequently adding to cognitive complexity.

## METHOD

### Apparatus, Participants, and Procedure

To objectively investigate the impact of environmental and display complexity factors on controller performance, a human-in-the-loop simulation test bed was developed (Figure 2). Since the subject pool consisted of college students, a simplified task was needed that contained realistic decision support tools, yet did not require years of expertise to operate. Thus the subjects’ task was that of a low-level surface manager of incoming and outgoing traffic, responsible for assisting a supervisor in managing personnel for baggage handling, ground personnel, and galley service. The radar screen in Figure 2 represents incoming and outgoing traffic in the terminal control area. The circle in the middle

represents the airport area. The timeline contains two essential elements, much like what is used in actual ATC timelines, incoming traffic (left) and outbound traffic (right). The incoming side of the timeline represents the time until the expected aircraft gate arrival. The outgoing side of the timeline represents the time that an aircraft begins loading passengers and baggage at the gate until it becomes airborne. Each aircraft label contains the flight number, number of passengers, number of baggage items, assigned gate number, velocity (when airborne) and altitude (when airborne).

After signing consent forms, subjects completed a tutorial and three practice scenarios. They then began the randomly assigned 18 test sessions, which lasted approximately 3.5 minutes each. Subjects were required to monitor both the spatial display and timeline, and answer questions from their superior through datalink (text message) communication. Subjects were also required to notify their superior when aircraft of a particular airline entered the middle circle.

### Experimental Design

Two independent variables were used to represent environmental complexity, number of aircraft (10, 20, 30) and arrival pattern (sequential vs. non-sequential.) Aircraft number has been cited throughout the literature as a leading source of complexity. In the context of the timeline display, arrival pattern was included as an additional environmental complexity factor because it could affect a controller’s ability to effectively search for information. Those aircraft that maintain their

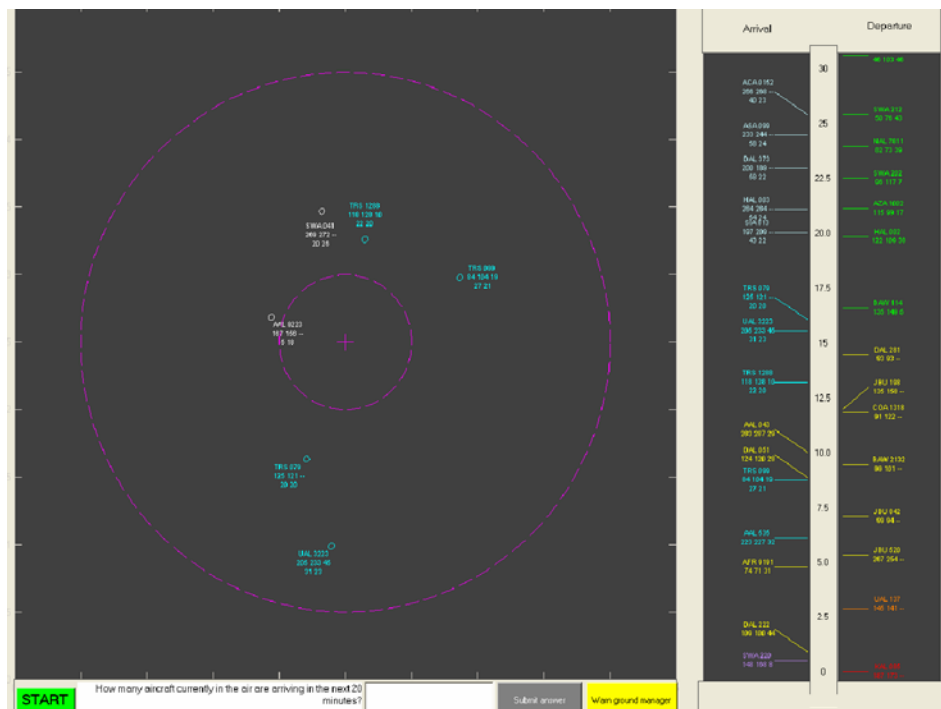


Figure 2: Test Interface

relative positions in the timeline are easier to track than those aircraft that appear to “jump” on the timeline, e.g., those aircraft that are put into holding patterns, disrupting the expected flow of traffic. The display complexity factor was the number of color categories used to represent information about incoming and outgoing aircraft (3, 6, 9).

The first dependent variable was answer accuracy, measured through questions in an embedded datalink tool. The subjects were asked questions such as, “How many aircraft will depart in the next 20 minutes?” These required subjects to calculate or derive information from multiple sources, e.g., the number of aircraft at their gates. In addition to answering questions, subjects were required to notify the supervisor when they first noted that a flight of a certain carrier entered the outermost radial circle on the spatial display. Failures to recognize this situation resulted in an error of omission, which is the other dependent variable. The statistical model used was a 3x3x2 fully crossed ANOVA and the 18 scenarios were randomly presented to a total of 29 subjects.

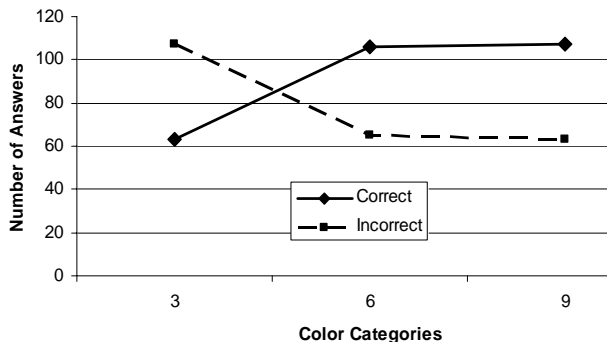
## RESULTS

The increase in color categories actually improved the answer accuracy, although there was no difference between the use of six or nine color categories (Figure 3, Pearson Chi-Square test,  $p < .001$ ). In general, wrong answers increased with increasing a/c levels. Measures of association using Cramer’s V are reflected in Table 1.

**Table 1: Accuracy Measure of Association**

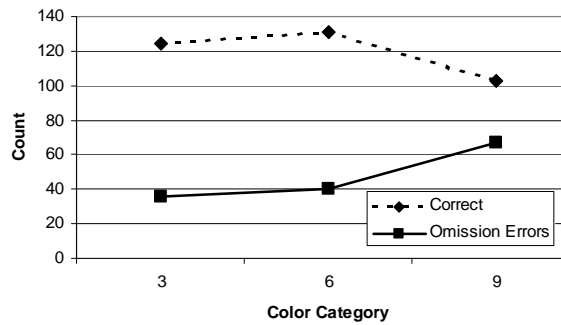
	Accuracy
Color Categories	.240 ( $p < .001$ )
Planes	.275 ( $p < .001$ )
Arrival Pattern	Not significant

For the errors of omission analysis, a Wilcoxon Signed Rank Test showed that the difference between the two samples (correct notifications and errors of omission) was significant ( $p = .009$ ), and for all independent variables, correct answers exceeded errors of omission. Figure 4 represents the overall correct notifications as compared to the errors of omission for the color categories. A Mann-Whitney test between the errors for the six and nine color categories



**Figure 3: Accuracy**

was significant ( $p = .001$ ), as was the Mann-Whitney test for a/c which showed a significant increase between 20 and 30 a/c. Subjects’ errors of omission increased when the arrival patterns were non-sequential, and the difference was significant (Mann Whitney,  $p = .036$ ). Given that all three independent variables showed significance through non-parametric testing, further investigation was warranted to determine the magnitude of any significant relationship. Association testing using the Kendall tau-b statistic revealed significant associations for all three variables, as shown in Table 2.



**Figure 4: Omission Errors - Colors**

**Table 2: Omission Error Association**

Factor	Association	Significance
Color Category	.330	$p < .001$
Planes	.355	$p < .001$
Arrival Pattern	-.293	$p = .001$

## DISCUSSION

### Environmental Complexity

The aircraft number factor was included because it represents a primary source of environmental complexity for controllers. In general answer accuracy decreased and errors of omission increased as the number of aircraft increased. Increasing numbers of entities for consideration is a known significant component of cognitive complexity (Edmonds, 1999), so result is expected.

Traffic flow is another commonly cited source of ATC complexity (Majumdar & Ochieng, 2002), so this environmental complexity factor was represented through sequential and non-sequential arrival patterns. Arrival pattern was not a significant factor for answer accuracy but it did significantly affect subject’s errors of omission, however, to a lesser degree than both planes and color categories. Arrival patterns did not directly cause errors of omission, but non-sequential patterns increased search time, and thus increased overall workload which diverted attention from the monitoring task.

### **Display Complexity**

Color coding is a design intervention meant to mitigate complexity and aid controllers in expeditious and safe handling of aircraft. For the answer accuracy category, color coding did significantly improve correct answers from the three to six color category, but reached a plateau at six so nine color categories provided no additional benefit. The analysis of errors of omission in the context of color categories provides evidence that using more than six color categories can introduce performance problems. When nine color categories were represented, errors of omission increased significantly from three and six categories which were essentially the same in error rates.

While number of aircraft exhibited a slightly stronger association for errors of omission, color categories was a significant contributor to errors of omission, more so than arrival rate. While increasing color categories do not “cause” people to forget actions, they do require that controllers spend more time in search and mapping tasks, and thus take away time from other tasks and increase the likelihood that a subsequent will be forgotten. This is an important finding because color coding is a design intervention meant to mitigate complexity, not add to it.

### **CONCLUSION**

Investigation of environmental and display sources of complexity revealed that increasing numbers of planes affected subject performance slightly more than color categories, however, traffic arrival patterns were not as strongly associated with degraded performance. This finding is important because the use of color in displays is meant to reduce environmental complexity, not add to it. These research results highlight the importance of understanding sources of complexity in human supervisory control. Displays are the primary visual mechanisms through which controllers build mental models, however, as demonstrated in this study, even a simple addition of color categorization can significantly influence controller cognitive complexity.

### **ACKNOWLEDGEMENTS**

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