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# PREDICTIVE AIDS AND MENTAL MODELS UNDER FREE FLIGHT: PROCEED WITH CAUTION

Ashley Nunes[1] and Olivier St-Cyr[2]

[1]Aviation Human Factors Division, Institute of Aviation
University of Illinois at Urbana Champaign
Savoy, Illinois, USA

[2] Department of Mechanical and Industrial Engineering
Cognitive Engineering Laboratory, University of Toronto
Toronto, Ontario, Canada

This paper discusses the possible adverse effects predictive aid usage may have on a controller's mental model in a Free Flight environment. Free Flight is a concept that is aimed at increasing throughput in the National Airspace System. However, various studies have suggested that implementing free flight could result in a controller's situation model being adversely affected given the lack of predictability in this environment. Consequently, the usage of predictive aids has been suggested as a possible solution to this problem. However, there is a possibility that the usage of such aids may negatively affect a controller's underlying mental model and thus, reduce his/her the ability to predict system behavior through mental simulations. Drawing on the results from two studies, we argue that caution must be exercised when introducing predictive aids under Free Flight conditions, given the possibility that such usage may adversely affect the controller's underlying mental model, which can ultimately result in performance being compromised.

## INTRODUCTION

In recent years, efforts to reduce delay while increasing airspace capacity in the National Airspace System (NAS) have resulted in much interest being expressed towards implementing an advanced form of airspace management that reduces controller involvement. To ensure that controller performance does not suffer as a by-product of implementing such concepts, there has been a tremendous influx of new technologies aimed at helping controllers maintain their awareness of the traffic situation. So-called 'predictive aids' are designed to reduce cognitive demand by extrapolating the trajectory of aircraft based on current parameters. Research studies have been focused on assessing how such technologies affect controller performance. However, the same level of effort has not been extended to determining how such technologies affect a human's mental representation of a system. That is, operators must be able to extract key functions and relationships from their mental model and use this knowledge to solve problems when they occur. In that sense, the mental model concept and the usage of predictive aids are interrelated and offer unique research possibilities.

## BACKGROUND

Various categories of user compete for the finite available airspace (Hopkins, 1995). The duty of keeping such users apart while they share this airspace falls to air traffic controllers; therefore, the primary goal of the air traffic control (ATC) service is to provide for the safe, orderly and expeditious flow of air traffic through the NAS. In order to maintain safe separation between aircraft while facilitating efficient traffic flow across regions of airspace, controllers rely heavily on their 'mental model' of the ATC system.

### Mental Models

Wilson and Rutherford (1989) pointed out that the phrase 'mental model' has been used in many different contexts, resulting in confusion among mental model researchers. Even today, there is no explicit definition for the term mental model (Hagert, 1985). Since there is no commonly accepted definition of mental models, researchers often define mental models to fit their own research purposes (Ok-Choon and Stuarts, 1995). Accordingly, for the purpose of the present paper, an internal mental model will then be defined as "the knowledge that one holds about the external reality" (a system), which is used in different contexts to undertake problem-solving strategies through predictions, inferences, and possible actions.

Rouse and Morris (1986) proposed that an internal mental model could be explained with the black box analogy. The main idea behind this analogy is that the mental model is actually the black box. In other word, knowledge that a person holds about a system will fill the black box and explain the possible relations between input and output. The black box analogy brings an interesting definition of mental models as pointed out by Rouse and Morris (1986). They stated that a mental model (the black box) includes knowledge about the system to be controlled, about the properties of disturbances to be expected to act on the system (environment), and about possible criteria or strategies to control those disturbances. Kieras and Bovair (1984) came to the same conclusions by defining a mental model as the understanding of how a system works, with respect to its internal structures and processes. Studying mental models using the black box analogy helps in understanding two important concepts:

*Level of understanding*: when faced with only input and output, operators have to use their understanding of the system to establish mappings and relationships between the two. Operators' knowledge will often come from their own internal mental model. Indeed, it is believed that predictions and problem-solving aptitudes are highly dependent on mental models (Gott, Lajoie, and Lesgold, 1991).

*Predictions and problem-solving reasoning*: if the black box starts behaving in unusual ways (faults, unexpected situations), one can grasp how operators are going to use their knowledge of the system (mental model) to predict possible outcomes and achieve efficient problem-solving strategies.

To summarize, three important aspects to consider when studying mental models are: how operators understand the system, how their understanding reflects their internal mental model, and how they will use their knowledge (stored in the mental model) to predict outcomes and solve problems efficiently.

## The Controller's Mental Model

Redding, Ryder, Seamster, Purcell, and Cannon (1991) proposed a general mental model for the en route controller. The model is divided into three major categories, which depict the knowledge required to direct effective problem solving in the en route environment. Panels located in the *sector management* category contain information pertaining to current aircraft parameters, potential conflicts and pilot requests that the controller must be aware of. Information regarding the general state of the airspace as dictated by weather conditions, staffing, traffic volume, complexity, and personal factors are located in the *conditions* panel. Finally, knowledge of the structure of airspace and the air corridors that define it are stored in the *prerequisite information* panel. The model is unique in that it encompasses dynamic knowledge such as aircraft data, which constantly changes as aircraft enter and leave the sector, and static knowledge such as prerequisite information regarding separation minima between aircraft.

## Situation Awareness

Endsley (2000) argues that a mental model must be viewed as being representative of static knowledge about a system, versus the dynamic, functional representation proposed by Redding *et al*. (1991). This view enables us to distinguish between a controller's generic knowledge about the entire ATC system versus knowledge and understanding of the *present state* of the system. Endsley (1995) defines the current state of the mental model as the situation model, which is an extraction of time and event specific information from the underlying mental model. Recognition of the situation model is important because it encompasses components of the process and state known as Situation Awareness (SA). Endsley defines SA as being the perception of the elements in the environment (level 1), the comprehension of their meaning (level 2), and the projection of their status in the near future (level 3). In the ATC domain, an operator's ability to maintain safe separation between aircraft is dependent on the achievement and maintenance of good SA. The controller must be able to effectively extract relevant information (such as aircraft position, type and speed) from the radar screen, comprehend what it means at the present time, and determine what it could mean in the future.

## Free Flight and Predictive Aids

As air traffic increases, it has become clear that the airspace infrastructure is being pushed to its breaking point. Controllers are faced with the challenge of providing a safe service to an ever-increasing number of aircraft and it seems likely that if air traffic grows at its current rate, the frequency of accidents will also increase as a result of gridlock in the system. In order to meet industry demands and improve efficiency, the Federal Aviation Administration (FAA) is examining shared-separation responsibility as a future operations concept (Endsley, Sollenberger, Nakata, and Stein, 2000), more commonly known as 'Free Flight'.

Free Flight (FF) in the United States is a FAA strategic goal for system capacity and for Air Traffic

Services to improve accessibility, flexibility, and predictability in the national airspace in order to reduce flight times, crew resource, maintenance, and fuel costs (Gore and Corker, 2000). Under FF, aircraft would no longer be restricted to flying air corridors, which comprise only 5 percent of available airspace (Endsley *et al.*, 2000). Since its conception in the early 1990's, the FF concept has evolved producing a variety of interpretations of what it could mean in the future ATC system. Regardless of the interpretation, all forms of FF call for the dissolution of the current route structure. In doing so however, the controller's mental model of the pattern of traffic flowing through the sector may be adversely affected. The normal route structure provides a great deal of information necessary for predicting how aircraft will transition across airspace and with whom they might have separation problems (Endsley *et al*., 2000). To help controllers anticipate an aircraft's trajectory under FF conditions, predictive aids have been suggested as a possible solution. The simplest forms of the system extrapolate the future trajectory of an aircraft based on current operating parameters. The positive effects of predictive aids on SA and controller performance (as evidenced by a multitude of measures including Situation Awareness Global Assessment Technique (SAGAT) scores and reaction time respectively) have been well documented (see e.g. Endsley *et al*., 2000; Nunes, 2002; Remington, Johnston, Ruthruff, and Romera, 2000).

## THEORETICAL CONCERNS

In reviewing studies that tackle the effects of automation on human performance in ATC, there has undoubtedly been a great deal of emphasis on SA. This approach is not without merit as lapses in SA are not tolerable, especially in a domain like ATC. However, a potential shortcoming of this approach may be the fact that almost too much emphasis has been and currently is being placed on SA while not enough is being done to consider the effects of predictive aid usage on the underlying mental model. After all, it is plausible that while measures may suggest that SA has not been compromised, detriments to the underlying mental model may be occurring, and if this were the case, researchers would not be aware of it unless an attempt was made to measure it. The cause for such detriments can be better understood by considering Anderson's (1996) notion of production rules. Anderson proposed that procedural knowledge (the knowledge associated with how to do something) is represented in small units called production rules and that retrieval of these rules is strengthened through repeated exposure. In an environment where a predictive aid is present, a different set of production rules must be executed to account for the presence of automation. When such rules are executed consistently over a period of time, the likelihood of correctly retrieving those rules associated with a 'non predictive aid environment' may decrease. The importance of retrieving these rules would however only be evident when the predictive aid fails and human intervention is necessary. In such complex situations, human intervention requires the operator to learn, acquire knowledge and problem-solve, efficiently and effectively, highlighting the need to consider and measure the underlying mental model.

### Mental Model Considerations

When a user is looking for a piece of information, he or she will look at the map and extract visual structures through perception. Cooper (1989) provides a good explanation of the underlying connections between visual structures and mental models. According to her, people do not only construct information from visual structures, but also send the extracted information to their current mental model in order to establish relationships between their mental model and the immediate environment. This information can then be used to solve problems, predict the behavior of the system, and determine if the system portrays a true representation of constraints present in the physical world.

Mental models also play a role in learning. It has been suggested by Moray (1999) that mental models help users to reason about complex systems and thus, facilitate the learning process. A study conducted by Kieras and Bovair (1984) showed that learning is affected by an understanding of the processes that describes the internal mechanisms of a system. Having a mental model of a system will contribute to the learning processes and will also ensure that people remember the characteristics, operations, and relationships present in the system.

Finally, knowledge acquisition and problem solving abilities are also related to mental models. Moray, Lootsteen, and Pajak (1986) conducted a study on acquisition of process control skills. They found that the first step towards acquiring process control skills is to understand the nature of the process to be controlled. They also pointed out the importance of mental models in learning process control skills, postulating that operators rapidly acquire a mental model of the process dynamics. By studying mental models, Moray *et al.* (1986) were able to deduce, to some extent, what operators learned in order to control the system more efficiently.

To summarize, mental models are influenced by the visual structures portrayed on the computer display. These will help operators better understand the system to be controlled and thus, have an effect on the learning process. Knowledge acquired about the system is then going to be organized in a meaningful way so that operators can efficiently control the system efficiently. Thus, one of the primary concerns when designing predictive aid displays must be to ensure that the Graphical User Interface (GUI) does not inhibit learning and long term retention. Wickens (1992), for instance, has argued that interfaces based on direct visualizations may actually reduce long-term learning and retention, which would have a direct impact on the operator's mental model. Thus, while displaying external visualizations based on direct perception might reduce the operator's mental efforts (Vicente and Rasmussen, 1990), it may not force the human to think extensively about the processes governing the system and thus, he/she may not completely understand the system's functionalities and relationships. Because of this reduced depth of processing, the operator's mental model might not be as complete as it should be. This is why mental models should be measured when conducting experiments in which display aids are being tested.

## EMPIRICAL FINDINGS

In an industrial process control domain, St-Cyr (2002) conducted a study to determine the impact of two different graphical displays of a thermal-hydraulic process simulation on mental models. The first interface was based on the physical structure of the system while the second was based on the Ecological Interface Design (EID) framework (Vicente and Rasmussen, 1992) and displayed information based on direct visualization.

Eighteen university students served as participants in the study. They were trained for four hours on the DURESS II (Dual Reservoir System Simulation) thermal-hydraulic process simulation operated via a visual display. Each participant's mental model was then assessed using several knowledge elicitation techniques (see St-Cyr, 2002, for more details).

In one knowledge elicitation measure, participants were asked to use their mental models to mentally simulate and predict future system states on a pen and paper exercise (interface independent), without being able to look at the interface they were trained on. A One-Way Analysis Of Variance (ANOVA) showed a close-to-significant result: $F(2, 15) = 2.850$, $p = 0.089$. Least-Significant Difference (LSD) Post-Hoc analyses suggested a possible significant trend between the Physical interface and EID interface groups, showing that the participants trained on the Physical interface were better at predicting future system states than the participants trained on the EID display ($p = 0.031$).

In the ATC domain, Nunes (2002) conducted a study to asses the impact of a predictive aid on controller performance in a Direct Routing (DR) environment under varying airspace load. The predictive aid in this study extrapolated the future trajectory of an aircraft and displayed it graphically to the controller. Direct Routing (a derivative of the FF concept), was defined as being an environment where aircraft utilized linear routes of travel across sectors of airspace and could not deviate from them without prior controller consent.

Twenty ATC trainees were recruited from the Air Traffic Management program at Embry Riddle Aeronautical University, Florida for the present study. Subjects viewed an hour long ATC simulation that was representative of a DR environment. Their task was to evaluate pilot requests for deviation from a current trajectory and to determine whether granting the request would result in a conflict. The most complex situation arose when the pseudo pilot requested an altitude that was free but an intermediate altitude was occupied (Conditional Request). In this case, the controller had to initiate a climbing procedure to an intermediate altitude for the requesting aircraft. An incomplete within-subjects design was used for the study and two independent variables were manipulated. They were display presence (no display and display) and airspace load (low and high). In the 'no display' condition, subjects had to respond to pilot requests using the radar screen alone whereas in the display condition, a predictive aid was also provided to assist them with the task of request evaluation. Display presence served as the between subjects variable and airspace load as the within subjects variable. The first half hour of the simulation represented low load and the second half hour high load. Dependent variables included SA and overall performance, as evidenced by SAGAT, response time and decision accuracy scores.

A Multivariate Analysis of Variance (MANOVA) revealed that SAGAT scores did not vary between display conditions ($F(6,13) = 0.51$, $p > .05$). Additionally, the interaction between display presence and traffic load for response time was significant ($F(1,58) = 13.3$, $p = 0.00$) for all types of requests, suggesting that the cost of traffic load on response time was greatly amplified when no display was present. However, closer scrutiny of results revealed that whereas scores got better as a function of time in the simulation for the 'no display' subjects, this was certainly not the case for those subjects using the aid. In fact, scores of the latter group remained fairly consistent through the study. Moreover, those scores for pertaining to the most complex type of request (Conditional Request) actually fell from 93% under low load to 73% under high load. While not significant, this trend in results certainly does call into question the effectiveness of using the aid for solving complex problems even though the main effect for decision accuracy scores ($F(1,18) = 3.78$, $p < .01$) and decision time ($F(1,18) = 16.5$, $p < .05$) pertaining to conditional requests was significant, in favor of using the aid.

## DISCUSSION

The results from the above two studies are quite intriguing. Results from St-Cyr (2002) suggest that the Physical interface group was better than the EID group at using their mental model to predict system behavior in the absence of any interface. One possible justification to these results could be explained by the fact that an EID display presents an externalized mental model of the system. Since the ideal externalized mental model was already presented on the computer display, it could mean that the operator followed the computer display without having to mentally simulate the system's relationships, since those one were already portrayed. On the other hand, the Physical interface might have asked operators to think and simulate the system's relationships, which were not portrayed on the GUI. In that case, participants of the Physical interface group were forced to run possible sets of solutions through an internal mental model, as opposed to running possible solutions through the externalized mental model, presented on the EID display. This observation is similar to results obtained in Christoffersen, Hunter, and Vicente (1998), who pointed out that EID can lead to the acquisition of deep knowledge and better performance only if participants take the time to reflect on the feedback they receive from the display. In contrast, if participants engage in surface learning, EID can lead to shallow knowledge, even though performance will not be inferior to the Physical interface.

Results from the second study are just as compelling. Post experiment interviews revealed that controllers in the 'no display' condition used traffic load as a medium for dealing with pilot request. They suggested that as the number of aircraft on a screen increased, so do the number of reference points for making trajectory extrapolations, which helped them in making decisions. This is an example of a strategy they used for dealing with complex problems, particularly conditional requests, in the absence of using automated aids. Formulation and utilization of this strategy forced the controller to first understand the problem, predict the outcome and then problem-solve; tasks that draw on information from the underlying mental model.

Controllers using the aid however, were not required to develop such strategies to deal with complex requests given the presence of automation and in all probability did not develop these strategies. This may explain why their scores for the most complex type of request (conditional request) did not increase over time but rather fell under high load, without a significant increase in response time (which was certainly the case for the 'no display' group). This result suggests that while SA (as evidenced by SAGAT scores) was not affected by display condition, 'aided' controllers may have not have fully understood the information being displayed on the screen nor did they think through the problem, but rather processed the information at a very shallow depth (for more detail on levels of processing, see Craik and Lockhart, 1972). Shallow processing in turn may have taken place because the predictive aid was designed to present the controller with a direct visualization of the situation, an aspect of interface design that Wickens (1992) has argued against, citing concerns over reduction in long-term learning and retention. The need for designing an interface in this manner, particularly in ATC however, has been grounded in the notion of reducing cognitive demand for the controller, but as previously suggested, following this thought process results in the human not being be forced to extensively think about the processes governing the system and as a result, the human may not completely understand the system's functionalities and relationships.

In sum, results presented in this paper outline two important considerations previously discussed with the black box analogy. First, one must ensure that operators of complex systems possess an adequate level of understanding of the system. Second, operators must also be able to use this knowledge in order to solve problems and predict outcomes when faced with uncommon situations.

## CONCLUSION

The importance of an operator's mental model as a medium for guiding the establishment of relationships between objects, learning, knowledge acquisition and problem solving has been well established and results from the studies by St-Cyr (2002) and Nunes (2002) highlight the need to measure mental models in empirical research when evaluating new technologies; this, regardless of the design framework that has been adopted. Given the current trend to utilize predictive aids under FF, it is imperative that this recommendation be considered during the empirical stage of product development for the cost of not doing so will be measured not monetarily, but in the number of lives lost.

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