ARRIVING FROM DELPHI AT O'HARE: PREDICTIVE COGNITIVE ENGINEERING IN THE O'HARE MODERNIZATION PROJECT AND BEYOND

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This paper describes a cognitive modeling effort for the O'Hare Modernization Project (OMP). Beginning with a statement of the problem, it describes how cognitive modeling was used to measure the mental workload and work time of controllers running various positions at O'Hare International Airport, both under the current airport configurations and a future set of configurations (proposed in the OMP). The O'Hare case is used as an exemplar of the type of data that can be acquired with relatively simple cognitive models

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O'HARE INTERNATIONAL AIRPORT

There's a sticker on the tower cab door at Chicago's O'Hare International Airport. It reads in a plain language typically reserved for the truth, "The world's busiest." It is no misstatement of fact or idle boast. And, if current projections are to be believed, it's only going to get busier. From the tower cab today, the taxiways look like city streets, with multimillion-dollar taxicabs lined up on Mike in nose to tail traffic. For those who have never caught the view from O'Hare's tower before, it is really quite unreal.

The demand on O'Hare has created a distinct need for more capacity in the form of more slots. Because of O'Hare's importance to the National Airspace System (NAS), this strain is felt not only there, but throughout the system. One effort aimed at easing the strain is the O'Hare Modernization Project (OMP). A proposed multiphase project, it would move O'Hare from a one tower operation typically using three to four active runways, to a three tower airport typically running six to seven active runways.

A change like this gives rise to a seemingly innumerable list of issues and because O'Hare is interwoven in the NAS, it can affect passengers for flights leaving Los Angeles and maintenance workers removing snow from a runway in Memphis. This study, however, focuses on the concerns of a group who will feel an immediate impact from any changes at O'Hare - the tower controllers.

Beyond simply looking at the change in the number of aircraft a controller handles, O'Hare was interested in addressing issues like mental workload, changes in work time, and changes to controller strategy. These questions will eventually be addressed in multi-million dollar simulation efforts. However, before moving forward with those, O'Hare wanted insight into what some of the important issues may be, thus helping to make the most of any time spent in the simulator. Providing answers to O'Hare meant predictive results, without the benefit of simulation. To get at these results, cognitive modeling was employed. While they do not provide the final word on all questions, the models did begin to bring some answers into focus and frame the questions in a way that will make them easier to address in a simulation environment.

COGNITIVE MODELS IN THE AVIATION DOMAIN

In the Quantitative Formal Models of Human Performance special section of Human Factors (2003), Byrne and Gray called for Human Factors practitioners to engage the engineering portion of the profession through the use of models of human performance that go beyond traditional subjective measurement, into a deeper, more quantitative understanding of human factors issues. Unfortunately, cognitive modeling is a unique language, and is often either perceived as too difficult to understand or too limited to be useful in applied settings. Cognitive modeling need not be that complicated, and its applicability is limited largely by the knowledge of the modeler, rather than by the model framework.

In this lecture, the process of creating and analyzing simple, and yet powerful cognitive models will be outlined in the context of the questions raised by O'Hare. This process should be of interest to those in aviation because so much of what goes into creating, designing, and evaluating effective aviation systems depends on our understanding of how pilots, controllers, and the like will interact with them. Cognitive models have the ability to predict how humans will interact, for example, with avionics that don't yet exist or procedures that have never been flown. In specific application, they allow for truly objective measures of workload and the prediction of memory based errors, learning times, and task execution times.

It is hoped that this discussion will provide a concise introduction to the use of simple cognitive models in the aviation domain, the types of results those models can provide, and the effort that goes into creating them. This paper, then, is not about the results of the study per se, but the process of retrieving those results. It is not about what the recommendations that were to O'Hare, but the nature of those recommendations, and their applicability to common aviation issues.

METHODOLOGY

Beginning with gaining a basic understanding of the tower controller's tasks at O'Hare and moving forward to the creation of cognitive models of controllers working in an ecologically valid environment, the method established for generating these models will be detailed.

Initial Cognitive Task Analysis

The initial Cognitive Task Analysis (CTA), developed by MITRE and O'Hare staff, took advantage of previous work done in this area (Alexander et al, 1989). The intent of the CTA was to gain enough of an understanding of the controllers' tasks as to be able to identify what data should be collected during the observation period. Using documents provided by O'Hare and the work done by Alexander et al, a CTA was created for each of the primary controller positions at O'Hare. Upon completion of the CTA for each position, results were sent to O'Hare staff for their review and updated based on their comments and suggestions.

For the purposes of this study, the CTA acted as a decision inventory, identifying why and when controllers make certain decisions in the current airport configuration. Each CTA depicted the primary decisions a controller would have to make, the location of the aircraft on the airport surface when that decision was made, the information and tools required, and a categorization of that decision.

Observation

Based on the results of the CTA, the observation was structured to capture key controller decision events, when they occurred, how often they occurred, and what tools were used. The observation period, which took place over the course of a week in the O'Hare Tower, included both day and night observations. Data was collected during the observation periods using a specially developed PDA program, a digital video camera, or both.

Cognitive Models

With the key decision events analyzed in the initial CTA and data on timing and frequency collected in the observation period, the process of building cognitive models could begin. The first models constructed were of controllers working

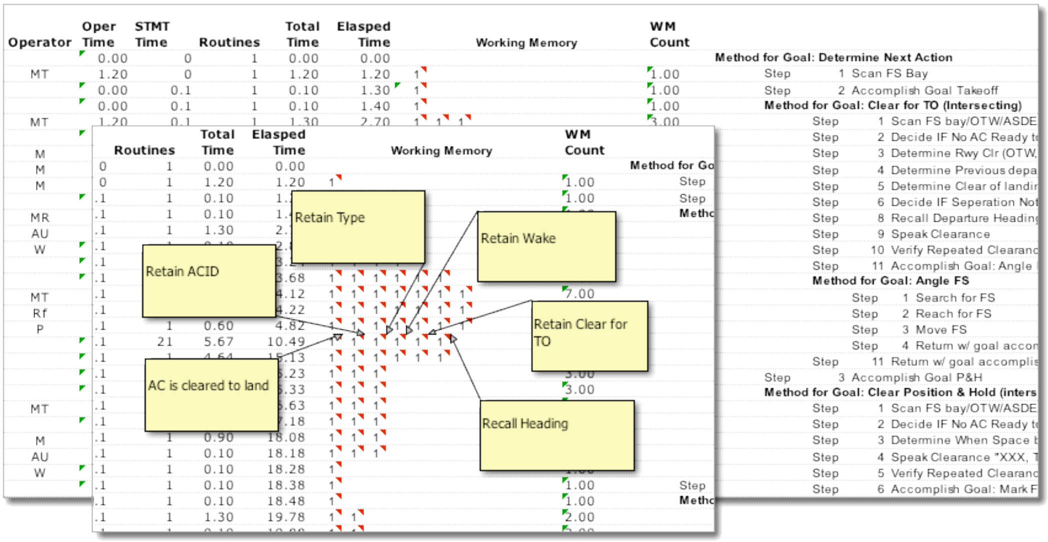

Figure 1 - Cognitive Model with Working Memory

various positions in the current airport layout. These will be referred to as the baseline models. Following the completion of the baseline models, predictive models of controllers working aircraft in the proposed future environment were constructed. The results from each allowed for a comparative analysis of mental workload and work time in the current and proposed future airport layouts.

Cognitive Models were developed using a variant of Goals, Operators, Methods and Selection rules (GOMS) known as Natural GOMS Language (NGOMSL). These models were also extended to model mental workload using working memory counts (Estes and Masalonis, 2003 and Estes, 2001). Figure 1 shows an example of one of the cognitive models, with working memory contents for one step in the model highlighted. It should be noted that within a couple of days someone can become familiar enough with NGOMSL that he or she is able to construct rather complicated models (Kieras, 1996). Learning how to model working memory is even less difficult, and could be taught in a matter of hours

One cognitive model was completed for each local controller in three existing O'Hare configurations (X, B, and Weird) and two proposed future configurations (East and West). Models of ground controllers working inbound and outbound traffic were also constructed for the current and proposed future O'Hare layout.

In order to more clearly understand model construction, it may be helpful to dissect a particular task. As an example, consider the task of clearing an aircraft for takeoff. During the CTA, the basic steps for delivering this clearance were set as a framework for the model. It was determined that once an aircraft was in position and holding and separation was adequate, the controller would issue a takeoff clearance

Using observation data, details about the nature of the clearance itself, when it was delivered, and timing of interaction with flight strips could be derived. With this information, it is possible, using the cognitive model, to look at the task at a finer level of granularity in order to determine cognitive demands placed on the controller.

In the case of the takeoff clearance, those demands begin when the takeoff goal is fired. That goal calls a method, which includes the process for accomplishing the takeoff goal and the sub-goal of angling the flight strip. As the model proceeds, memory process involving what must be retained in Working Memory or recalled from Long Term Memory are instantiated in the model. This

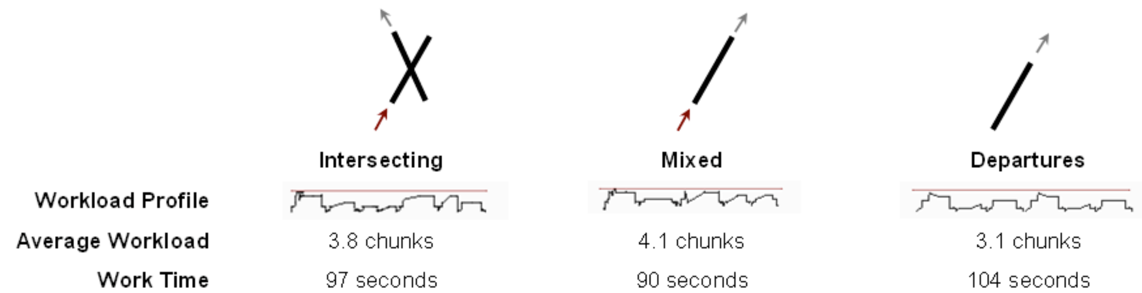

Figure 2 - Cognitive Model Outputs

includes representing items like the departure heading for the runway given the aircraft's destination, wake vortex, the aircraft type, and the runway configuration.

The task of clearing an aircraft for takeoff is called during a scenario, which the modeler creates. For the purposes of this study, the scenarios used were taken directly from observation at O'Hare during peak traffic periods. For a local controller working intersecting runways, this means a steady, alternating queue of aircraft, one departing from a runway and one cleared to land on another runway. The events in the model, then, are dictated by the scenario and the task fired when the controller perceives conditions are right in the environment to do so.

Final Outputs

With the cognitive models completed, comparative results can be generated. These results, which are quantitative in nature, focus on mental workload of the controller and work time, both as a function of the configuration and controller position. Mental workload can, obviously, be comprised of a number of elements, many of which are not captured by the cognitive models.

In this analysis mental workload is measured and predicted by working memory load. Working Memory is widely known to be a cognitive bottleneck and source of error (Lerch et al, 1989). The straight line in the graphs shown in Figure 2 indicates a working memory load of seven chunks. It should be noted that studies have shown air traffic controllers can typically have a recollection of up to ten aircraft (or ten working memory chunks) after leaving their shift (Bisseret, 1970). For this analysis, we became interested in what drove working memory peaks, and why those peaks did or did not exist in the future airport layout

Typical outputs from the models are shown in Figure 2. Comparisons of controller workload can quickly be made, as well as the work time for controllers working each runway type. At the task level, the results provided insight into the workload and time demands placed on controllers in operations like Land and Hold Short Operations (LAHSO). LAHSO, for example, did increase controllers work time because of changes in the clearance that must be issued, but had no effect on mental workload. During the process of creating the model, it also became apparent that the models would give insight to O'Hare management on staffing requirements because they could "see" how workload would be distributed according to the number of controllers that staffed the proposed future layout.

DISCUSSION

The simple cognitive models described in this paper are nothing new. They have their roots in research by Card, Moran, and Newell that began more than 20 years ago (1983). However, perhaps because of a perception that the models are complex or limited in their applicability, human factors practitioners in the aviation domain have rarely made good use of them.

In total, the entire study took four months, most of which was invested in developing comfort with the modeling process. For quick answers, it has been possible to produce limited, but informative models in as little as 12 hours, as was accomplished in a project investigating Controller-Pilot Data Link Communications (CPDLC). All that was required was a simple description of what the prototype would look like (it does not exist yet) and a few hours spent with an operational expert.

At O'Hare, the models measured what had widely been assumed by those involved in the O'Hare Modernization Project as immeasurable. That is, what the impact of the proposed future layout would be on a controller's mental workload. Further, it provided O'Hare the opportunity to consider other issues like the amount of staffing required to ensure an evenly distributed and manageable workload for each controller. Cognitive modeling is, of course, not a magic bullet. It is important to note that this methodology, like all methodologies is limited. NGOMSL, the model used in this study, assumes expert, error free behavior which may be unacceptable for a wide variety of projects. However, if the questions are amenable to the limitations, cognitive models can provide powerful data, simply.

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