An Emergent Behavior Model of Complex Human–System Performance: An Aviation Surface-Related Application

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ZUSAMMENFASSUNG

Fortgeschrittene Technologien koennen stark abschwaechende Effekte auf menschliche Fehler haben. Wird allerdings der Nutzer nicht angemessen waehrend der Technologieentwicklung beruecksichtigt, treten unvorhergesehene Effekte auf das menschliche Verhalten und Systemschwaechen hervor. Es ist daher wichtig, fruehe Anzeichen, die die Systemsicherheit beeinflussen, zu qauntifizieren und vorherzusehen. Eine Methode, die die Quantifikation von Mensch-Maschine Systemen ermoeglicht, ist ein integriertes menschliches Verhaltens Model. Dieser Bericht wird demonstrieren, dass Verhaltensmerkmale aus "human-in the loop (HTL)" Simulations Daten genutzt wurden, um als Basis fuer ein Software Tool zur Modellierung von praediktiv auftretendem menschlichem Verhalten zu dienen und Mensch-Maschine Leistungs Vorhersagen zu erzeugen. Dieses Software Tool heisst "Air Man-machine Integrated Design and Analysis System (Air MIDAS)". Air MIDAS zeigte wie ein Agent durch eine simulierte Umgebung angeregt werden kann und erfolgreich Verhaltensentwicklungen generieren kann.

ABSTRACT

Advanced technologies can have powerful mitigating effects on human error. However, if the user is not adequately considered during the technological development, unforeseen effects on human performance and system vulnerabilities emerge. It is important therefore to be able to quantify and predict precursor events that impact system safety. One enabling methodology for human-system quantification is termed the integrated human performance model. This paper will demonstrate that performance modifiers shown by human-in-the-loop (HITL) simulation data were used as the basis for the predictive, emergent human performance modeling tool Air Man-machine Integrated Design and Analysis System (Air MIDAS) in generating human-system performance predictions. The Air MIDAS software tool demonstrated an agent's sensitivity to a simulated environment through successfully creating emergent behavior.

INTRODUCTION

Many digital human modeling software tools currently examine one aspect of human performance, namely the human physical representation. The representation of anthropometrics is indeed a very important consideration in developing new design concepts but is not the only consideration. New designs especially those being developed for complex systems are likely to incorporate some form of technology that utilize or relies on a human's cognitive capabilities. Often times, this technological crutch takes the form of automation. Automation increases precision and economy of operations but has the unanticipated effect of increasing a human operator's cognitive, perceptual and attentional workload (1). The increase in workload often negates some of the benefits afforded to the system from the use of automation. Operators may miss critical events in the environment due to a number of unexpected human-automated systems issues such as unevenly distributed workload, new attentional demands, and new coordination demands among operators[1]. When critical physical events are missed, no response is possible (2,3). One aspect that is characteristic of all human behavior therefore is that the human performer is required to "think" in order to perform successfully in the operational environment. This cognitive functioning however interacts with the physical characteristics of the human operator and the environmental characteristics of the world to impact the behavioral output of the human operator. The result of this interaction then feeds-back into the interpretive cognitive world. The interaction of these intertwined characteristics needs to be properly considered in designs so as to design the safest systems that maximize the human operator's capabilities. One methodology that enables such evaluation is known as computational human performance modeling. Human Performance Modeling allows studies to be conducted early in the design phase (often at the concept development stage) (4,5). One specific tool that enables the insertion of cognitive characteristics into a physical world is a tool called the Air Man-machine Integration Design and Analysis System (Air MIDAS). Air MIDAS has been designed primarily for the examination of aviation system-related behaviors, the use of automation, and the effect of this automation on multi-crew operating environments and performance (4,5). One particularly critical operating environment where system complexity, automation and multi-crew coordination requirements exist in the aviation domain is airport surface operations.

BACKGROUND: THE TAXI DOMAIN

A recently completed series of research projects that included a number of high fidelity human-in-the-loop (HITL) simulations conducted at NASA Ames Research Center (ARC) found that pilots made navigation errors when taxiing on complex airport surfaces (6,7). These errors have been attributed to perceptual limitations, loss of situation awareness and cognitive factors. The perceptual factors include missing critical environmental characteristics which results in an operator error. The situation awareness factors have demonstrated themselves when pilots incorrectly thought they were in one location on the complex airport surface when they were in fact in a different location. The cognitive factors include declarative or working memory errors, communication confusions, or intent incongruencies.

The development of a valid model of human error behavior applied to surface operations was recently undertaken. The model development process was based on information that was provided by NASA ARC's Human Error Modeling Program (6,7) and from a detailed analysis of existing literature on the etiology of human error (8). Air Midas modeling predictions have been validated for certain scenarios with Air Traffic Management data (9,10, 11). Here this architecture is

[1] For a complete review of the unexpected human-automation integration effects, please see (1).

used to generate predictions of human operator performance in airport surface operations. The effect of the change in information available and the resultant potential for human error due to the uncoordinated mental representations among agents in the system motivated this research.

NASA ARC research efforts have focussed on creating dynamic models of human performance and, more recently, on anticipating human error in complex human-system performance. The creation of an integrated representation of the humans operating in the environment was required. This integrated representation modeled a critical point in surface operations. The Chicago O'Hare Airport (ORD) that was used in a 1999 full mission human-in-the-loop (HITL) simulation (7) was generated in a human-out-the-loop (HOOTL) simulation model.

BACKGROUND: THE MODELING DOMAIN

In order to generate a sufficiently valid model of behavioral prediction, a representation of the equipment (physical aircraft), the crew-station and external environment was created at varying levels of fidelity depending on the importance of the information for updating the agent's world. A number of mechanisms and control mode structures exist within the Air MIDAS computational framework (12). The control modes within the Air MIDAS structure that have the potential to be sensitive to manipulations include memory errors and their effect on the simulated crew's internal representation. This internal representation is contained within a structure termed the updateable world representation (UWR). Two types of error mechanisms were represented.

- The first error type, memory load errors, occurred as a result of information competing for working memory (WM) space. When there were a number of items needing to occupy WM, one item in WM needed to be shifted out of the limited capacity store by the subsequent information from the pilot or from the controller communication. This information was lost if it was not written down to a location from an actively available list from which the agent was able to visually encode the information (for example a taxi clearance).

- The second error type, declarative memory errors, included errors that occurred when agents forgot the active procedure as a result of having too many procedures of the same type operating at the same time. The occurrence of this error was modeled by scheduling the simulation to concurrently invoke similar procedural demands (dropped tasks = memory loss).

The errors represented above were created by increasing the number of items in WM and by increasing information transfers through "active" or ongoing procedures. Each type of error emerged as a result of the scenario requirements and demands placed on the agent's cognitive structure. Each type of error was therefore not created deterministically; rather each error type emerged based on the environmental requirements and loads that were associated with the performance requirements of the agent.

MEMORY ERRORS

Two memory decay rates were incorporated into the human performance model's structural memory representation. Each decay rate was thought to invoke various levels of predicted agent performance. The decay rates within the model interact with the capacity limits of the agent's cognitive structure in a manner consistent with real human operators (13). Human operators consistently forgot 20% of the information encoded after one day and 50% of the information by the end of a week while additional evidence found that some encoded portions of information can also endure for extended intervals even when not actively rehearsed (14). The presentation of these results assumes that the agent is engaging in activities in an unaided condition (no memory aids). Activities in surface operations are assumed in this model to fail when the memory for those activities falls below 25% of initially encoded information. This reflects the decay memory trace algorithm used in the current examination. The memory trace is also influenced by the active elements that the agent must commit to memory. As demonstrated in Figure 1, the probability of recalling 25% of the information that was provided to the agent performing in the Low Cognitive Capability condition, would be at 12 seconds after the information was received by the agent (algorithm #1 – solid line). The probability of recalling 25% of the information that was provided to the agent performing in the High Cognitive Capability condition would be at 24 seconds after the information was received by the agent (algorithm #2 – dashed line). This difference in probability of recalling the information impacts the performance of the cognitive structure of the human performance simulation model.

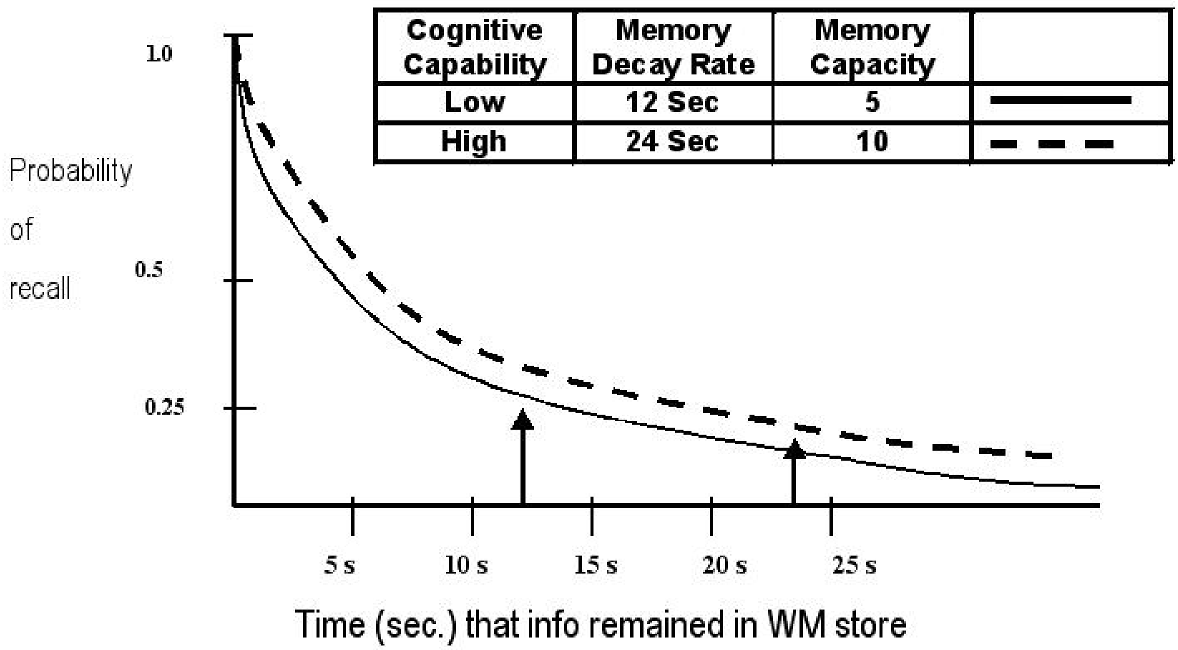

Figure 1. Temporal and storage capacity of Air MIDAS' working memory structure.

As seen in Figure 1 the cognitive performance of the agent is affected by increasing the time delay between the receipt of the information and the performance of a goal behavior (turning on the airport surface). The performance that is associated with this kind of output would take the form of increases in the time required for the cognitive structure of the agent to possess a probability of recall of 25%. This algorithm was used to assist in creating emerging errors from the Air MIDAS model and are reflected through the performance output. This algorithm was used in the Human Performance Model that was created for the taxi baseline operations.

METHOD

DESIGN AND PROCEDURE

Replicating the classes of error discovered from the HITL simulations required the development of a rich environment and a relatively complex set of procedures for the agents to follow in the simulation. A representation of pilot-pilot interaction, of Air Traffic Controller (ATC)-pilot interaction, and of the airport surface environment was built. A set of realistic landing procedures was modeled including: environmental monitoring, changing radio frequency, contacting ATC and listening to clearance, and inter-cockpit communication. The procedures, priorities, and decisions necessary to generate the observed behavior were produced by the model. Obviously, there were many variations on individual component processes (e.g., memory, decision, action scheduling, etc.) that could produce the observed error behavior. Selection and refinement of the appropriate processes to “predict” performance in similar circumstances was guided by integration of models of human contextual control and by taxonomic human error principles that have been developed. These predictions were examined with reference to similar incidents, and with reference to HITL simulation data in which procedural non-compliance has been observed. The first stage in developing the Air MIDAS model was to determine the environment causing the human performance model procedures to be invoked (the rules guiding the behavior of the agent).

HEURISTICS CREATED

A number of performance rules were created to guide the model in this simulation. These will be referred to throughout the ‘results’ section.

<u>Behavioral Heuristics</u>

1. Operating Under Uncertainty. Crewmember performs a “crosscheck” (re-updates the cognitive capability) and taxis until they see confirming information from the environment.

2. Operating Under Uncertainty Combined with Time Delay. Crewmember does not perform “crosscheck” (no re-update) and enacts a taxi “Direct to Gate”.

<u>Cognitive Heuristics</u>

1. Primacy effect. Information entering into the crewmembers’ Updateable World Representation (UWR) will be pushed out of memory by subsequent information entering the UWR if it exceeds the critical 7 +/- 2 memory limit (12,15,16).

2. Shared Intent Failure. UWR mismatch between agents in the simulation results in negotiation among agents to resolve the UWR discrepancy.

SCENARIO DETAILS

One operational environment from a series of scenarios utilized in the HITL simulation was selected as the environment to model in Air MIDAS. The taxi route possessed a complex taxiway geometry that served to increase the UWR of the agents. This route also required extensive communication among the agents in the simulation.

Human performance modeling and system vulnerabilities

Two human error structures within the cognitive representation in surface operations were modeled - memory errors and their associated resultant UWR error. Three agents were modeled (at differing levels of fidelity) in order to create an emergent, integrated and interactive human performance model. These interacting agents were modeled with different goals and responsibilities associated with their roles in system operations (see Figure 2). It was determined that modeling the three agents, the Captain (CA), the First Officer (FO) and the Tower ATC, would provide a realistic modeling environment and exercise some of the multiple crew coordination mechanisms within Air MIDAS.

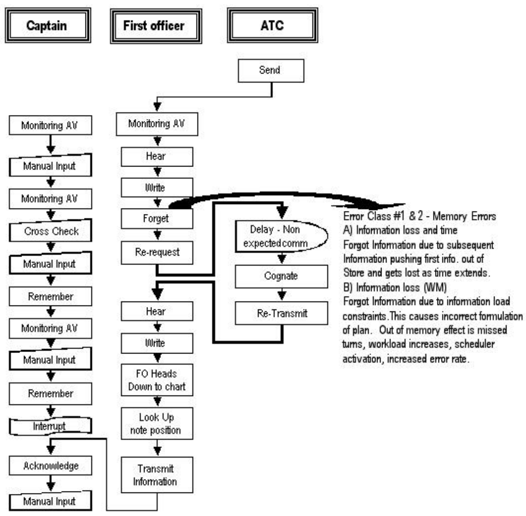

Figure 2. Scenario Overview Guiding Model Development.

Three agents, the CA, the FO and the ATC, were represented along with their procedures (8). Two activities demonstrated here are designed to serve as exemplars of the code within the Air MIDAS software tool. The high level static procedural representation noted in Figure 2 were used as the basis for coding the procedural representations termed “Parents Activities” required by Air MIDAS noted in Figure 3 below.

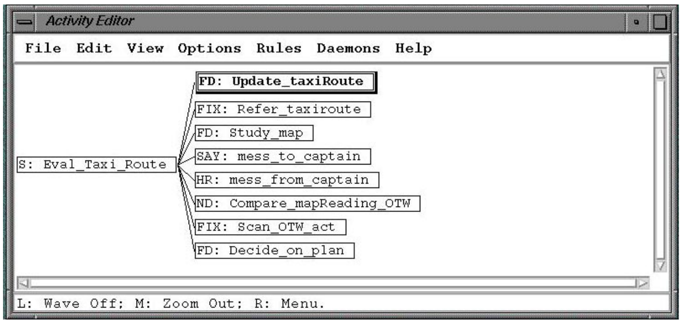

Figure 3. Air MIDAS screen snapshot of the editor representation of the "Evaluate Taxi Route" procedure.

Figure 4 demonstrates the Parent Activities that are coded in Air MIDAS. These parent or “leaf” activities are high level activities that trigger the onset, or spawn, the occurrence of the children or “sub-leaf” activities indicated in Figure 4.

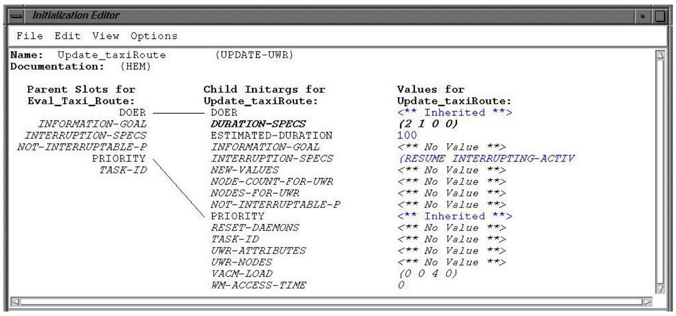

Figure 4. Air MIDAS screen snapshot of the sub-leaf activity "update_taxi_route".

Dependent and Independent Variables.

Three human performance metrics were of interest in this simulation. The first was the pattern of errors, the second was the occurrence of errors and the third was workload that was faced by the agents in the environment. Each of these individual elements was considered to be critical in the analysis of error for determining the conditions under which the error rate changes in response to operational changes. There were two independent variables in the current study – memory decay rate and information availability. The cognitive demands were represented through the memory manipulations of the Air MIDAS software in the decay rate and the capacity store. Decay rate was either high with a 12 second/5 element limit which comprised the low cognitive complexity variable or low with a 24 second/10 element limit which comprised the high cognitive complexity variable. The decay rates were representative of operator performance in complex environments (16,17,18). A second set of manipulations included the time that the ATC transmitted the navigation information (clearance) to the flight deck (thus the time the information became available to the flight deck) –24 seconds (low), 50 seconds (medium) and 80 seconds (high) from the runway turnoff. A total of ten seed-generated, Poisson distribution runs were completed for each of the experimental manipulations (cognitive complexity and information availability times) made in the simulation for a total of 60 runs.

RESULTS

The metrics of interest in this simulation include the predictions generated from the HOOTL simulation – the error rate, the agent's performance times, and the workload measures from the perspective of the flight deck. The error types that emerged included those errors resulting from memory overload, and those memory errors resulting from time pressure. An examination of the workload and the time to completion was indicative of an environmental effect on performance. Air MIDAS' sensitivity to the environmental manipulations was represented by the effect on system performance as a function of Air MIDAS' memory half-life.

ERROR PATTERNS

The error pattern that was predicted from the human performance model in the current experiment occurred at one of two locations along the airport surface of the taxi environment. Figure 5 demonstrates one pattern of error behavior and is termed Error Pattern #1. The error in Error Pattern #1 was predicted to occur at the first turn on the taxi surface following the aircraft's exit (turn) from the runway. An error on the first turn resulted in executing behavioral heuristic #2. This first turn error emerged due to the memory capability limitations and the time pressure involved in completing the goal behavior.

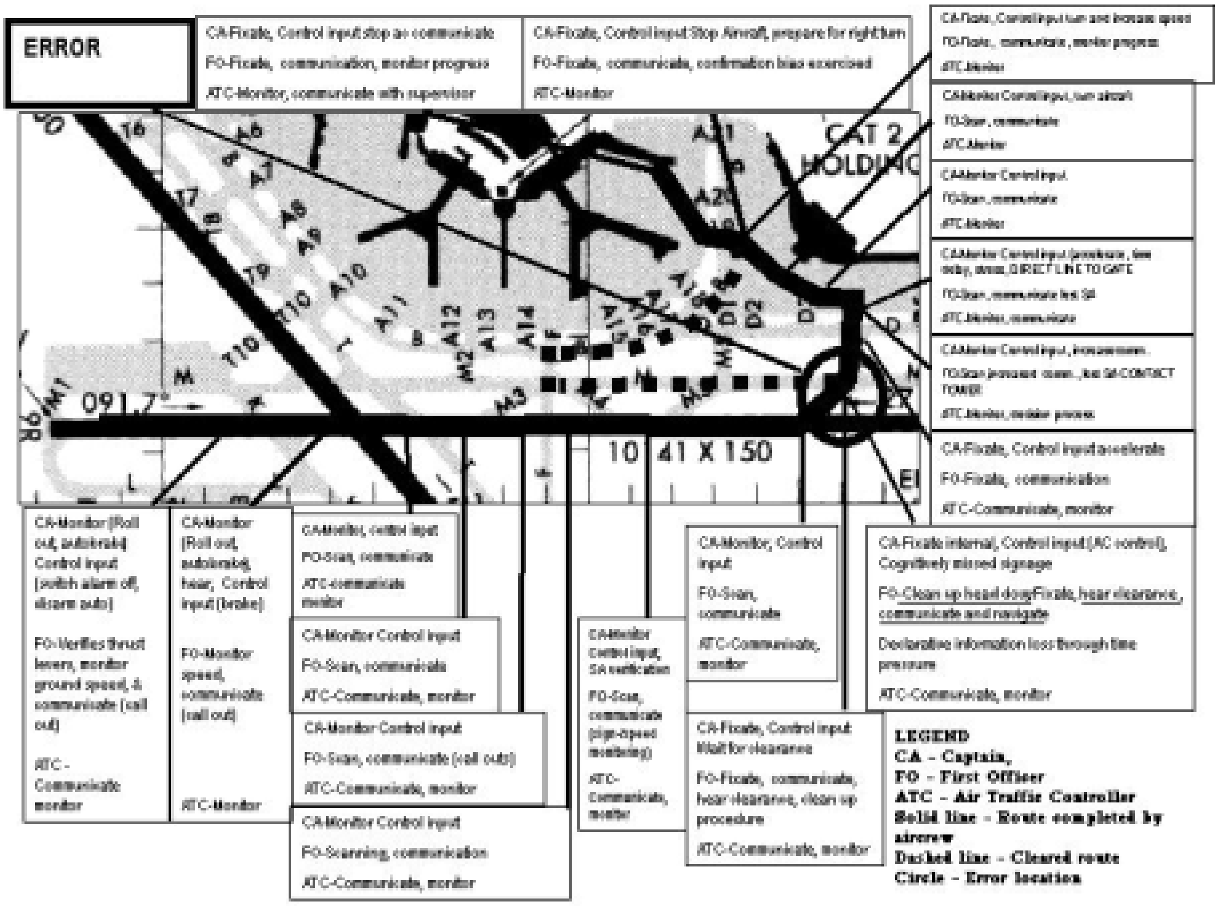

Figure 5. Air MIDAS Error at Turn #1 (Circled). Agent continued traveling straight but should have turned left onto the cleared route (dotted line). Error invoked direct line to gate heuristic as the agent recognized that they were lost. A representation of the activities coded and completed along the environmental timeline is included in this graphic.

Figure 6 demonstrates a second pattern of error behavior and is termed Error Pattern #2. Error Pattern #2 was predicted to occur at the second turn along the simulated route to the gate. An error on the second turn resulted in the termination of the simulation. Both Error Pattern #1 and Error Pattern #2 occurred due to memory decay rate and memory capacity of the agent in the simulation. Error Pattern #2 emerged due to a 'no recall' procedure where the agent had declines in the memory trace to a level where they could not gather the required information from the memory to complete the goal behavior.

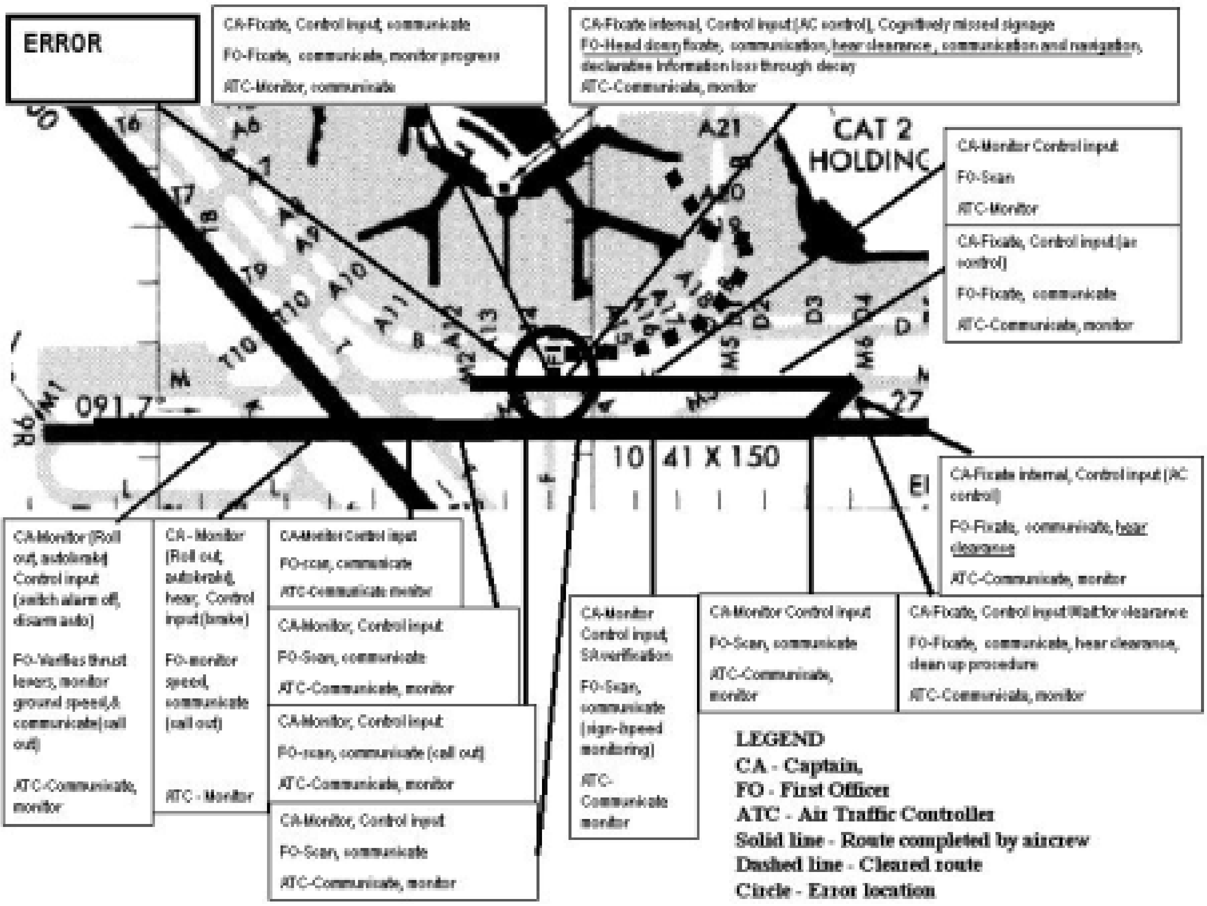

Figure 6. Air MIDAS Error at Turn #2 (Circled). Agent correctly made a left turn onto Taxiway "M" and traveled along taxiway "M" to Taxiway "F". Agent made error at Taxiway "F" as they did not stay on the cleared route (dotted line). Error resulted in simulation termination. A representation of the activities coded and completed along the environmental timeline is included in this graphic.

ERROR PREDICTIONS

A second performance metric in the current experiment included the percentage of runs that invoked a heuristic. Invoking a heuristic was considered to be indicative of the occurrence of an error because the HPM would "call" a rule to guide behavior only under conditions of uncertainty. The output measures were based on the manipulations that were made in the experiment – low and high memory decay rates, and the low, medium and high information availability variable. The human performance model predicted that errors would occur on every run and in every memory condition (frequency = 10) when collapsed across both turns modeled in the current examination. Although this was not fully expected nor consistent with human performance HITL data (6,7), the key to this finding is that the model is predicting the error onset (and its subsequent cause) and is calling for a rule to guide its behavior. The set of rules in the current instantiation did not include the onset of the communication and resolution between agents in the simulation. Had this rule been incorporated, the model would have been able to select among the three rule alternatives. Behaviors including communication would have emerged from the human performance model based on the environmental characteristics and the probabilities associated with the implementation of the rules surrounding the emergent behavior.

Figure 7 demonstrates that the human performance model did not predict any difference in performance at the Low Memory Capability condition for the ten errors that were observed. Differences were found between the heuristics invoked in the High Memory Capability condition suggesting that performance could be improved if information became available later in the scenario (at the 50 seconds mark of the simulation).

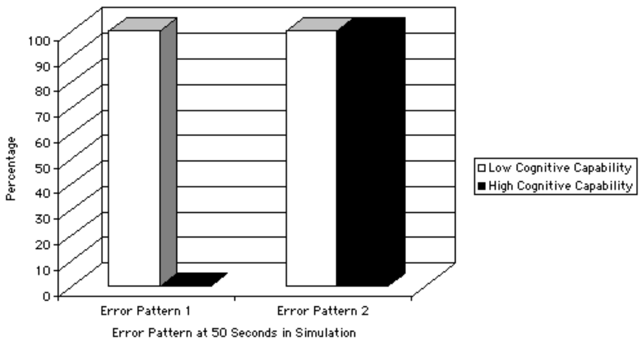

Figure 7. Percentage of time the heuristic was invoked as a function of time in the simulation (50 seconds).

Figure 8 demonstrates that the human performance model did not predict performance differences in the Low Memory Capability condition but that performance differences were found between the heuristics invoked in the High Memory Capability condition. This result indicates that performance was better when information arrived later in the scenario (this time approaching the 80 seconds mark of the simulation). The significance of no difference between the 50 and the 80 seconds times is that the cognitive structure responsible for the occurrence of the error is being accessed somewhere between the 24 and 50 seconds time period as there were no errors committed in the 24 seconds condition.

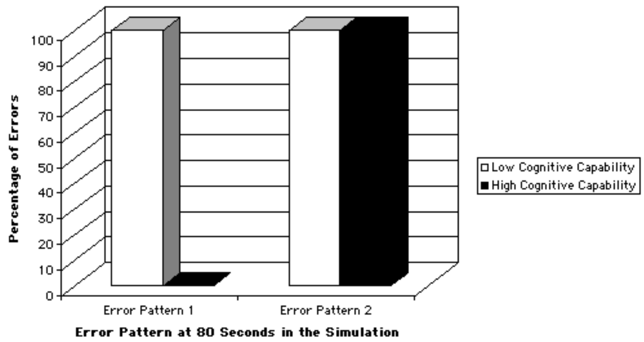

Figure 8. Percentage of time the heuristic was invoked as a function of time in the simulation (80 seconds).

WORKLOAD PREDICTIONS

A workload output along the visual, auditory, cognitive, and psychomotor modalities from the HOOTL HPM was obtained (Figure 9). The output measures were generated based solely on the memory manipulations that were completed in the simulation and were collapsed across the information availability manipulation.

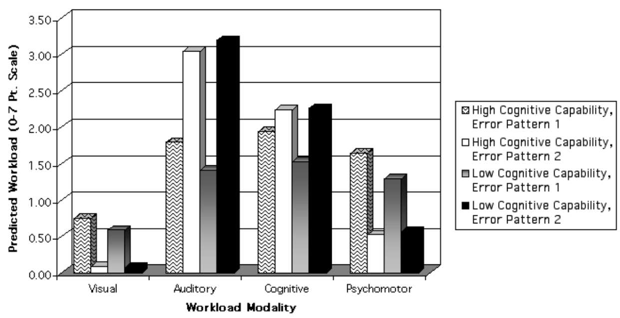

Figure 9. Predicted load levels (0-7 pt scale) within elements that comprise the HPM workload representation.

Figure 9 demonstrates that the agent's modality was differentially affected by the memory manipulations conducted in the current simulation. In considering the specific modalities, we can see that the visual demands were greatest in the Error Pattern #1, in a consistent pattern across memory conditions (low and high memory decay conditions). It can be seen that the auditory and cognitive demands were greatest in the Error Pattern #2. The auditory increase for Error Pattern #2 was due to increased communication between the virtual flight crew agents as they needed to refresh their memory store as time extended from the receipt of information to the time that performance was required. The increase in cognitive demands was found to be associated with Error Pattern #2 – this was an expected finding as the flight crew rely more on the internal memory structure for the accurate directions as opposed to using information immediately available within their cognitive store. When this cognitive representation is considered with the performance characteristics, it is interesting to note that the virtual flight crew agents forgot their navigation instructions when they relied solely on the cognitive structure embedded within Air MIDAS. Psychomotor demands were greatest in Error Pattern #1. This occurred because the agents were required to make physical inputs to turn the aircraft from the runway to the taxiway and this did not necessarily occur in Error Pattern #2.

DISCUSSION

The human performance modeling software tool predicts performance effects of varying environmental conditions and effects associated with information availability. The alignment of the system vulnerabilities with the human vulnerabilities provides the opportunity for erroneous performance to emerge. The use of the Human Performance Model (HPM) to study this emergent human-system vulnerability enables a cost and time efficient method to examine concepts associated with increasing system safety early in the design stage. In order to accomplish this however, HPMs need to accurately represent human psychological capabilities and system and environmental characteristics.

The behavioral predictions that emerged from Air MIDAS demonstrate that internal structures within Air MIDAS are sensitive to assumed psychological capacities and scenario demands. Procedural interruptions occurred when agents were faced with procedures that competed for procedural memory resources. These resources decayed across time and became lost if time extended beyond an acceptable upper time boundary (decrements by the WM decay rate on each tick of the Air MIDAS simulation). The delay that was associated with the information provision is consistent with information research that suggests that human memory traces degrade as delay increases (13) and alludes to the concept that HPM tools usefulness in determining design solutions. One such design solution could be that there is an optimal time when information should be made available to the agent. It can be hypothesized from this initial model simulation run that the “as needed” timing mechanism that may be active in this instance occurs at a critical decision point. This decision point is predicted to occur somewhere between 24 and 50 seconds in the initial simulation as there was a change in the predicted pattern of results. In the low information availability time with High Cognitive Capability there were no errors while in the high and medium information availability time with Low Cognitive Capability condition, 100% of the trials contained an error. This suggests that the agents need additional information to that information solely contained within the agent’s cognitive structure to successfully complete the goal behavior. The present modeling effort however, was initial and lacked sufficient fidelity from which to base real world design changes.

The procedural errors, manifested by incorrect turns, are consistent with the HITL surface operations simulation that found evidence of errors occurring because human operators omitted or substituted parts of a required taxi clearance to get to the gate, a procedural memory error (7). The HOOTL HPM predicts HITL procedural memory errors through its WM representation of WM load-related errors. Additionally to predicting the WM load errors, the HPM also predicts performance effects based on modifying the timing associated with the information presentation to the agent. This provides the model developers and the system designers with some insight into the timing associated with the human performance limitations and some insights into the causes of the various limitations. It is with this information that the system designers can then suggest design alternatives to maximize human performance with complex systems.

LIMITATIONS

One limitation of the current research is that the HPM conducted in this simulation did not quantitatively predict human performance in a consistent manner with the HITL simulation outlined (7). The differences that existed between the HITL research and the present modeling effort lie primarily in the manner in which the HPM was programmed to respond to lack of information. The model was programmed to call a rule to guide its behavior when the modeling software became aware that it did not contain the required information to complete a goal behavior. The set of rules contained a limited set of responses that could have been produced by the human performer. An augmentation to this series of rules is therefore required. It is suggested that the rule set be augmented to include a stronger dependence on the context and the environment that surrounds the agent performing in the emergent human performance model. Although there can be some explanation for the data patterns that are predicted from the Air MIDAS human performance model simulation conducted, care needs to be exercised in generating any conclusive findings until a full validation has been conducted with HITL data being compared to the HPM data.

FUTURE RESEARCH

There are three main directions that need to be considered in future human performance modeling research in this surface operations environment. The first direction is for a verification effort (19) of the human performance modeling structure that has been activated in this simulation. This verification effort will require that an examination of the structures that activate and the structures that fail within the integrated and emergent HPM are indeed representative of the actual HITL performance that characterize the surface operations environment. The second consideration is for a validation effort (19) between the HPM and HITL performance along the timing mechanisms and the workload predictions generated from the HPM. The final consideration for future research is to incorporate an 'augmented technologies human performance model condition' to enable within model comparison between the current simulation on baseline predictions and future performance predictions with advanced technologies. This comparison will enable a determination of the effect that the technological modifications will have on a HPM in a complex operating environment such as the one facing the NAS. The accuracy of the HPM predictions will need to be compared to the results from a study such as the one that was conducted (7).

CONCLUSION

A significant need exists for developing accurate models of human-system performance. Understanding the mechanisms that underlie human performance when human operators are completing complex procedures alludes to an understanding of the underlying structures that interact within the human operator to form emergent human behavior. The current paper outlines one methodology that attempts to explain human performance in computational terms, or virtual performance. The coupling between the job, the use of the automation and the human is critical if the tools that are being generated today will be useful in accomplishing the ultimate goal of accurately predicting human performance in the increasingly complex, and cognitively demanding work domain.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

Air MIDAS – Air Man-machine Integration Design and Analysis System

ATC – Air Traffic Controller

CA – Captain

FO – First Officer

HAIL – Human Automation Integration Laboratory

HITL – Human-in-the-loop

HOOTL – Human-out-of-the-loop

HPM – Human Performance Model

LTM – Long Term Memory

NASA – National Aeronautics and Space Administration

NASA ARC – NASA Ames Research Center

ORD – Chicago O'Hare International Airport

SJSU – San Jose State University

SOM – Symbolic Operator Model

T-NASA – Taxiway - Navigation and Situation Awareness

UWR – Updateable World Representation

WM – Working Memory